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MORTALITY OF FISH SUBJECTED TO EXPLOSIVE SHOCK AS APPLIED TO OIL WELL SEVERANCE ON GEORGES BANK

by

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ABSTRACT

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Mortality of Fish Subjected to Explosive Shock

As Applied to Oil Well Severence on Georges Bank

I. INTRODUCTION:

The use of underwater explosives as sound sources and in construction, demolition, and warfare has created concern about effects on fish populations. This concern has motivated considerable research and extensive literature has resulted. In addition to the reports directly concerned with biological effects there are many that discuss explosives as sound sources or report the physics of explosions underwater. We have collected, compared and evaluated various accounts of the effects of explosives on fish and other marine life, and make our report here. We have not performed any new experiments on fish vulnerability but have assembled and correlated data in order to make predictions of fish mortality from proposed explosive detonations and to estimate the significance of the predicted mortality. The information has been organized to answer, as well as possible, the following questions:

1. What types of vertebrates and invertebrates are affected?
2. What blast wave parameters correlate best with the probable mortality of the above groups?
3. Can the correlation be improved by parameters calculated from a combination of blast and fish dimensions?
4. Given the geometry of the situation, how are the parameters calculated?
5. With reference to Georges Bank and the proposed blasts, what is the maximum probable concentration of fish in the affected volume?
6. With reference to Georges Bank, what is the relative proportion of explosive mortality to other known causes of mortality?

II. TYPES OF FISH AFFECTED:

All authors agree that fish that have gas-filled swim bladders as a buoyancy organ are much more sensitive to blast damage than those without such an organ. This conclusion is based on comparison of explosive tests on spot, white perch, anchovy, Pacific sardines, salmon, trout, carp, bass, and several other species, all of which have swim bladders, with adult flatfish such as flounder and sole, which do not have swim bladders. Tests on oysters, crabs, and lobsters indicate that they too are quite resistant to blast damage. Dissections of blast damaged fish, birds, and mammals have shown that the injuries are usually associated with gas-containing organs. Of commercially important fish on Georges Bank, many, such as cod, pollock, haddock and hake have swim bladders and must be assumed to be at risk.

Mackerel and some other vigorous pelagic fish do not have swim bladders. The sacrifice of neutral buoyancy is probably an adaptation to permit them to make rapid depth changes. Negative buoyancy may be an advantage for some species that live on or near the bottom. Besides flatfish, some other bottom fish such as kingfish (Menticirrhus) do not have swim bladders. Sharks and rays belong to a class which did not evolve swim bladders. The species of this class that approach neutral buoyancy are lightened relative to water by large oil filled livers. Even though a species has not been tested, it is reasonable to assume that if it does not have a swim bladder it is more resistant to damage from explosive shock.

Fish with swim bladders are subdivided into physostomes that have a duct permitting fairly rapid release of gas from the bladder and physoclists without such a duct. Yelverton et al., 1975, have shown that fish with and without the duct do not differ in blast sensitivity. This finding is reasonable when one considers that the time constant of the small duct, though short compared with exchange through the blood and gills that is used by the physoclists, is nevertheless much longer than any blast wave. Thus, it does not pass a significant amount of gas during the transit of shock waves.

In general, invertebrates do not have gas containing organs and are considered to be resistant. But any form of life very close to the charge may be killed or damaged. Hardy (1956) reports on the use of dynamite to kill marine borers in wooden pilings. According to his report, six or seven sticks of dynamite four to eight feet from the piling is an effective treatment. We calculate that this would subject the borers to peak pressure of about 184 bar and an energy flux of about 10^5 joules/m^2 which is between 100 and 1000 times the levels that kill fish.

III. DAMAGE PARAMETERS:

a. Functions of fish depth, charge depth, explosive weight and slant range

Various functions of the blast wave have been suggested as damage parameters. If an ideal damage parameter were known, the probability of kill in a proposed blast situation could be predicted as a linear function of the parameter. Early papers suggested peak pressure, P_m, of the shock wave as such a parameter. The impulse, $I = \int_{t_o}^{t_c} p\,dt$ from first arrival time to surface reflection time t_c, the energy flux,

$E = \int_t^\infty p^2\,dt$ or the logarithm of any of these quantities could be a possible parameter. If probability of kill is apparently a nonlinear function of some simple parameter, the techniques of linear regression can be used with a transformed parameter which is a nonlinear function of the simple one.

In experiments where fish in cages have been exposed, where sufficient information has been given to calculate an explosion parameter, and where kill ratios or damage levels can be used to estimate probability of kill, the correlation coefficient of a regression line can be used as a figure of merit of the explosion parameter.

There are four data sets in the literature in which large numbers of fish were exposed under reported conditions that permitted us to make a fairly accurate computation or estimate of a number of possible damage parameters and to estimate probability of kill. Hubbs, Schultz, and Wisner (1960) reported an experiment which we analyze below as data set D. Yelverton et al., 1975, reported an experiment which we analyze below as data set C. Goertner (1978) analyzed a two part experiment reported in Gaspin, 1975, Gaspin et al., 1976, Gaspin, 1978A, and Gaspin, 1978B. This same experiment is also reported and analyzed by Wiley et al., 1981. Although this experiment was performed on two different dates with some difference in methods, we divide the data by the two fish species most often used and report the spot as data set A and the white perch as data set B. Data set A includes results from both of Gaspin's experiments; so does data set B.

Hubbs, Schultz and Wisner (1960, data set D) exposed fish in cages at a place where the water was more than 200 meters deep about 10 miles west of Mission Bay and Point Loma, California. Using explosive charges of nitrocarbonate, they exposed fish (mostly northern anchovy [Engraulis mordax] and Pacific sardines [Sardinops caerulea]) at depths from 1.2 to 172 meters and ranges from 15 to 213 meters. The charges, weighing 2.26, 4.54, and 11.3 kg, were detonated at depths of 1.5 meters or less. The fish were dissected immediately after exposure and results reported as percentage in which specific levels of damage were seen. Since the number of fish exposed in each cage was not reported we can only estimate the total number of fish exposed which seems to have been about 800. The authors report measured peak pressures that agree quite well with the similarity equations (Cole, 1948). Data set D summarizes our analysis of this report.

Data sets A and B are taken from experiments conducted by Gaspin and others in Chesapeake Bay opposite the mouth of the Patuxent River where the water depth is about 46 meters. Charges were at depths from 1.5 to 21 meters. Charge weights varied from .45 kg to 32 kg. These experiments have been reported and analyzed in several papers (Gaspin, 1975, Gaspin et al., 1976, Goertner, 1978, and Wiley et al., 1981). In the first experiment (July-August, 1973) there was not enough dissolved oxygen for fish respiration deeper than about six meters. In the second experiment (May-June, 1975) oxygen was sufficient and some tests were made with fish at depths up to 30 meters. The fish used were of many different species, but by far the majority were either spot (Leiostomus xanthurus) or white perch (Morone americana). Hogchokers (<u>Achirus fasciatus</u>, a kind of flatfish) proved to be very resistant as expected of a fish without a swim bladder. Oyster toadfish (Opsanus tau) which do have swim bladders were surprisingly resistant (possibly because their body tissues are very resilient). The spot and white perch exposures were, however, in the range of increasing probability of kill. Goertner (1978) published a detailed analysis of the 725 spot and 811 white perch exposures.

In data sets A, B and D the fish were dissected immediately after each exposure and classified by damage level. The damage levels were nearly equivalent - Hubbs describes them as follows:

0. No damage.
1. Only light hemorrhaging, principally in the tissues covering the kidney.
2. Gas-bladder intact, but with light hemorrhaging throughout the body cavity, with some damage to the kidney.
3. No external indication of damage, but with the gas-bladder usually burst. Hemorrhaging and organ disruption less extreme than in (4) and (5), but with gross damage to the kidney.
4. Incomplete break-through of the body wall, but with bleeding about the anus. The gas-bladder is almost invariably broken and the other organs damaged as noted under (5).
5. Rupture of the body cavity. The break is usually a slit just to the side of the mid-ventral line. Associated with this severe damage is a burst gas-bladder and gross damage to other internal organs. The abdominal contents are often completely lost or homogenized.

The dissection reports for data sets A and B were in terms of number of fish in a cage and number of those fish suffering injuries at each damage level or greater. For data set D a damage level was reported for each cage without details of injury to individual fish. For data set C detailed counts of the dissection results were not reported. The results for data set C were given in counts of killed and survivors after a two-week holding period.

To estimate probability of kill for reports A, B, D, we considered various statements made by authors about damage levels and survival and then chose the following formula:

$K = 1/210\ (.1 \times G + .25 \times H + .75 \times I + J)$ where

K = probability of kill

G = percent of sample at level 1 or greater

H = percent of sample at level 2 or greater

I = percent of sample at level 3 or greater

J = percent of sample at level 4 or greater

This formula counts 100% kill if all the fish are at level four or greater, approximately 50% kill if all are at level 3 and none at level 4, approximately 5% kill if all are at level 1 and none at any higher level. While these estimates may not be precise, they do rank the results in a way that is consistent with the following notes: Goertner (1978) states that free swimming fish that can be collected dead after an explosion all exhibit injuries of level three or greater. Yelverton et al., 1975, states that some survivors dissected after two weeks show evidence of burst swim bladders that have healed.

Data set C is taken from experiments performed by Yelverton et al., 1975, in an artifical pool about 46 meters by 67 meters by 10 meters deep. The sides were sloped to the central deep portion which was about 30.5 meters long by nine meters wide. A variety of fish species and sizes were exposed at depths from .052 to three meters and ranges from 6.1 meters to 44 meters. They used .45 kg spherical pentolite charges at depths of 3.0 or 1.5 meters; they report number of fish exposed and number killed at each cage. Fish were counted as killed if they did not survive as long as two weeks. 851 fish were exposed. In data set C we estimate probability of kill for each trial as number killed divided by total number exposed in the trial at a given location.

For all four data sets, we calculated various damage parameters for each exposure from the geometrical and charge data and performed regression analyses on the results.

If y is probability of kill and x is a parameter, then for a plot of experimental points (x_i, y_i) we find the straight line $y = m_y x_i + b_y$ for which $\Sigma (y_i - y)^2$ is a minimum. This is the regression of y on x which predicts the probable value of y when x is known. m_y is the slope and b_y is the intercept of this line. Alternatively, we find the straight line $y_i = m_x x + b_x$, i.e., $x = (1/m_x)(y_i - b_x)$ for which $\Sigma (x_i - x)^2$ is a minimum. This is the regression of x on y which predicts the probable value x when y is known. The two straight lines are not the same unless the experimental points have no scatter.

If r is the correlation coefficient calculated by standard statistical formulas, the fraction of the variance accounted for by the regression is equal to r^2.

We have calculated the regressions of probability of kill on damage parameter and damage parameter on probability of kill for log P_m, log I, and log E (Figures 1-7 and Table I). Only the logarithmic regression lines have been plotted because regressions of the logarithmic parameters gave higher correlation coefficients, and this result seems reasonable since biological responses are usually related to the logarithm of stimuli.

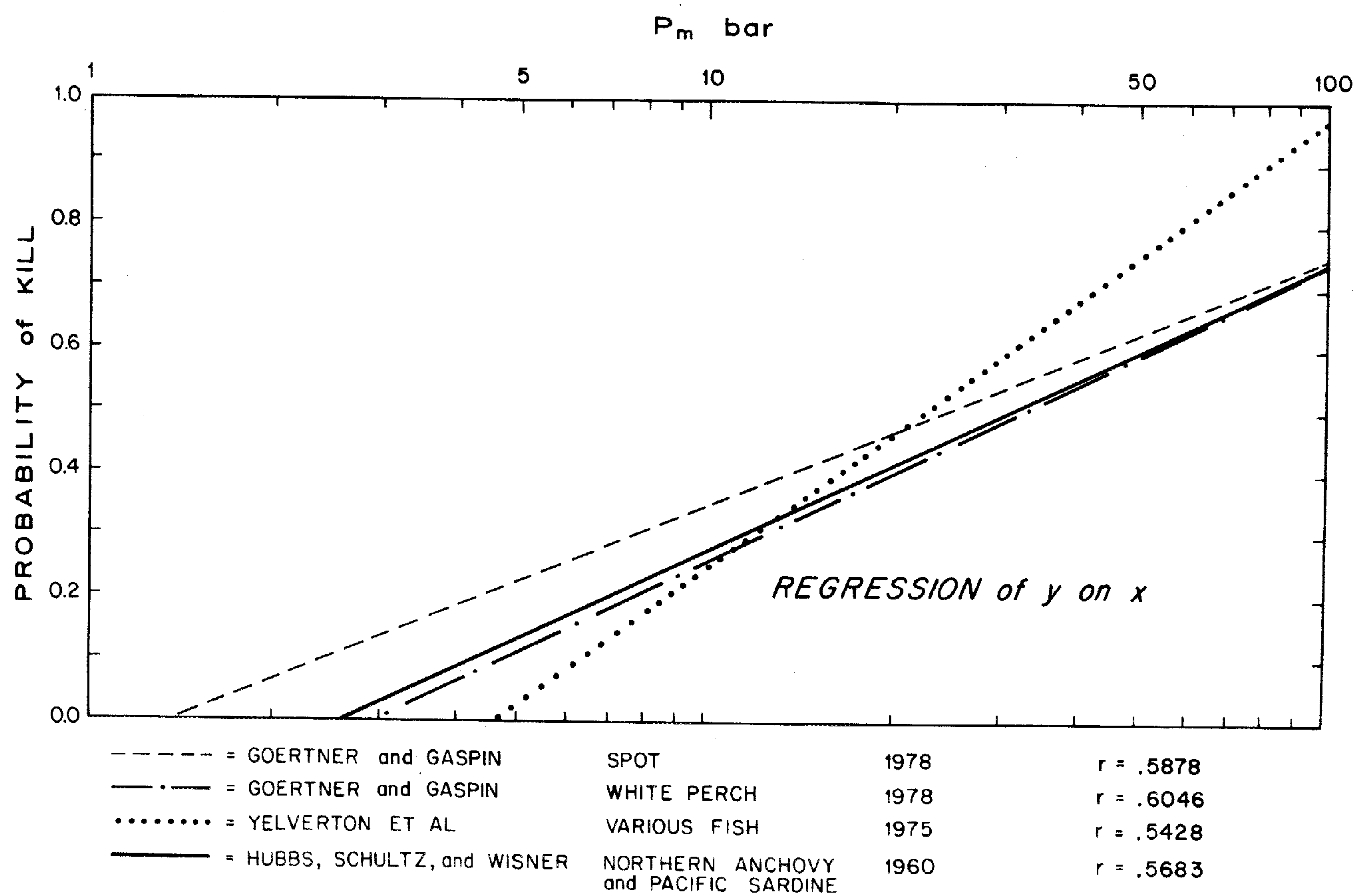

FIG. 1 Regression of probability of kill on log P_m.

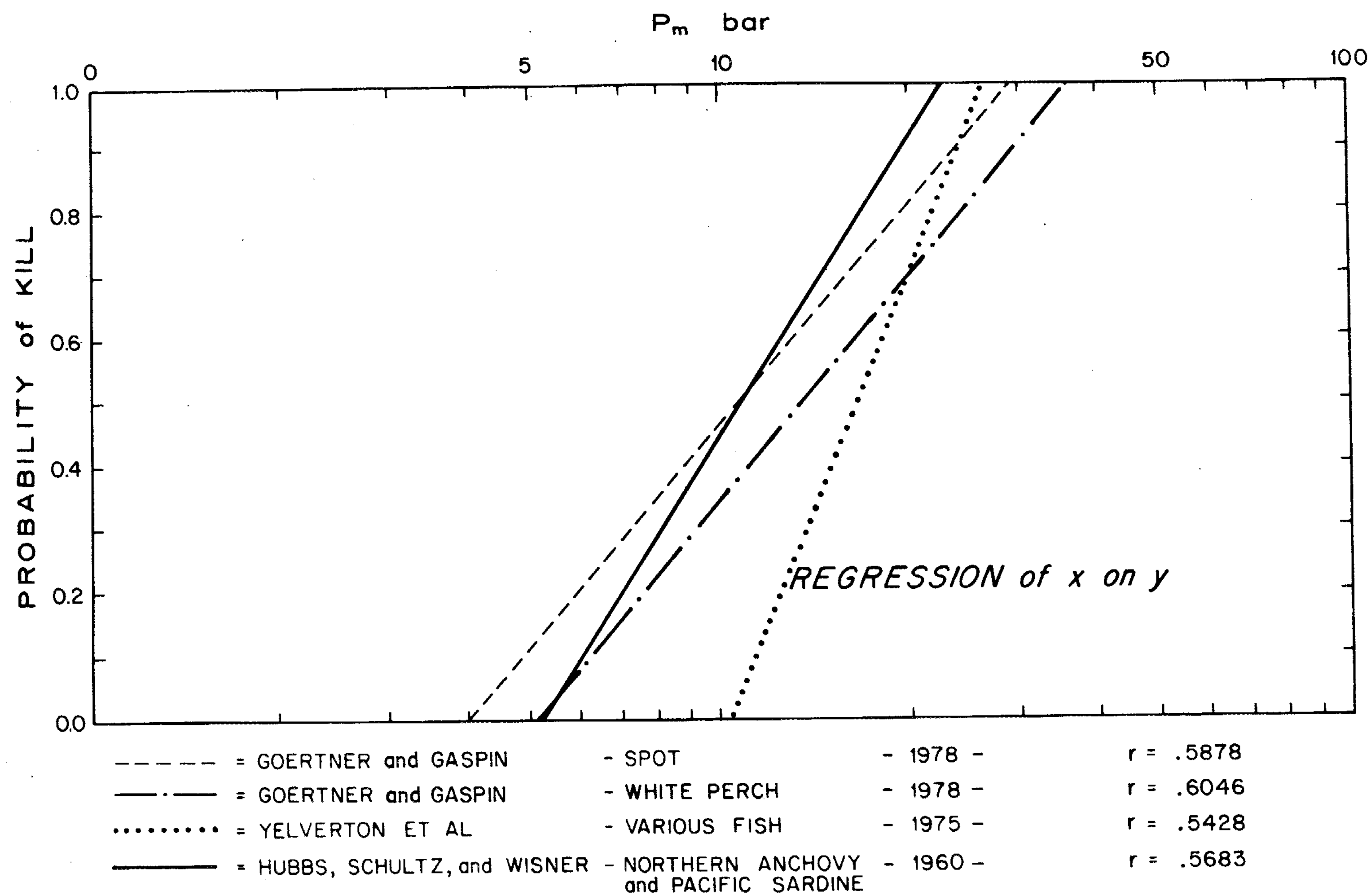

FIG. 2 Regression of log P_m on probability of kill.

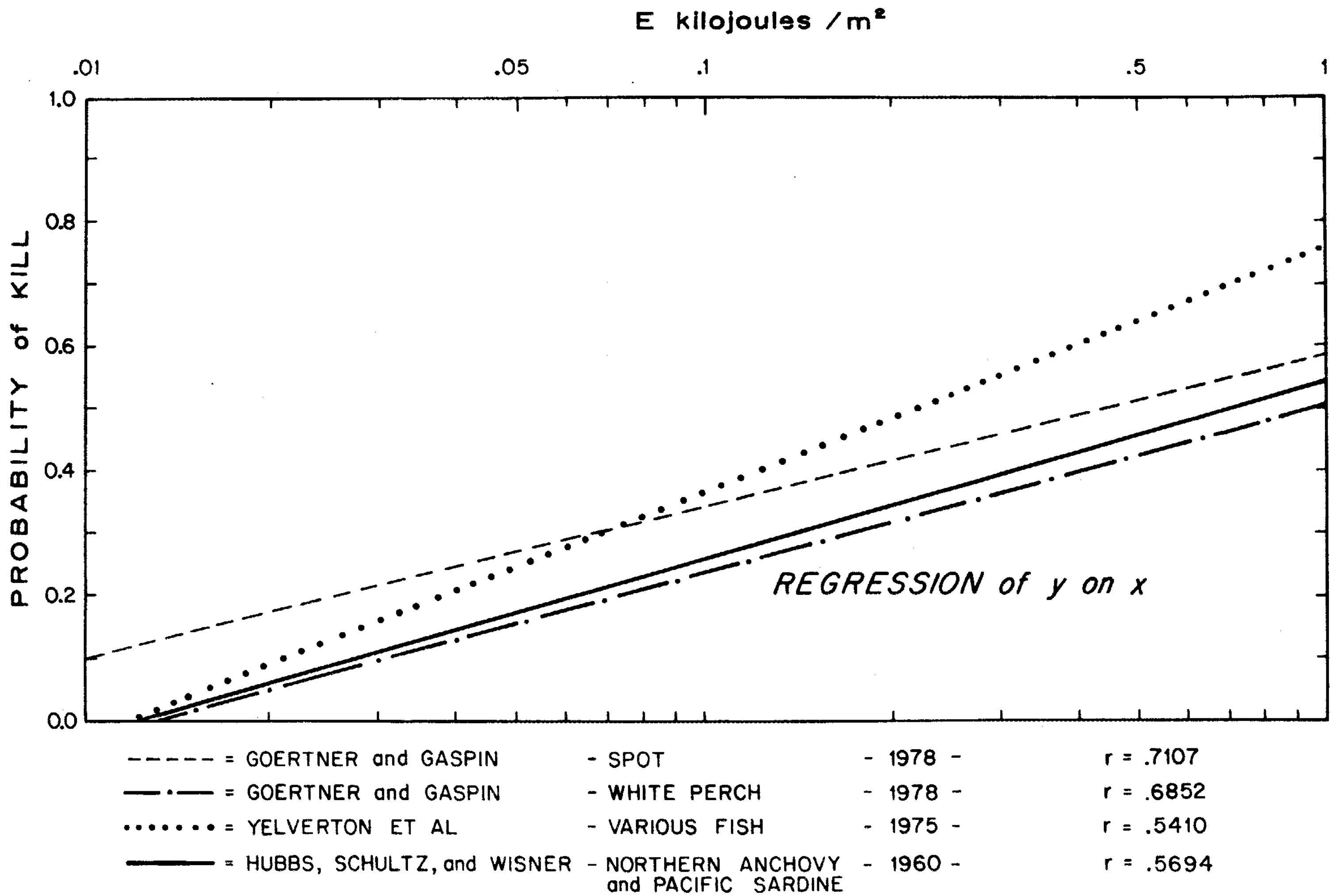

FIG. 3 Regression of probability of kill on log E.

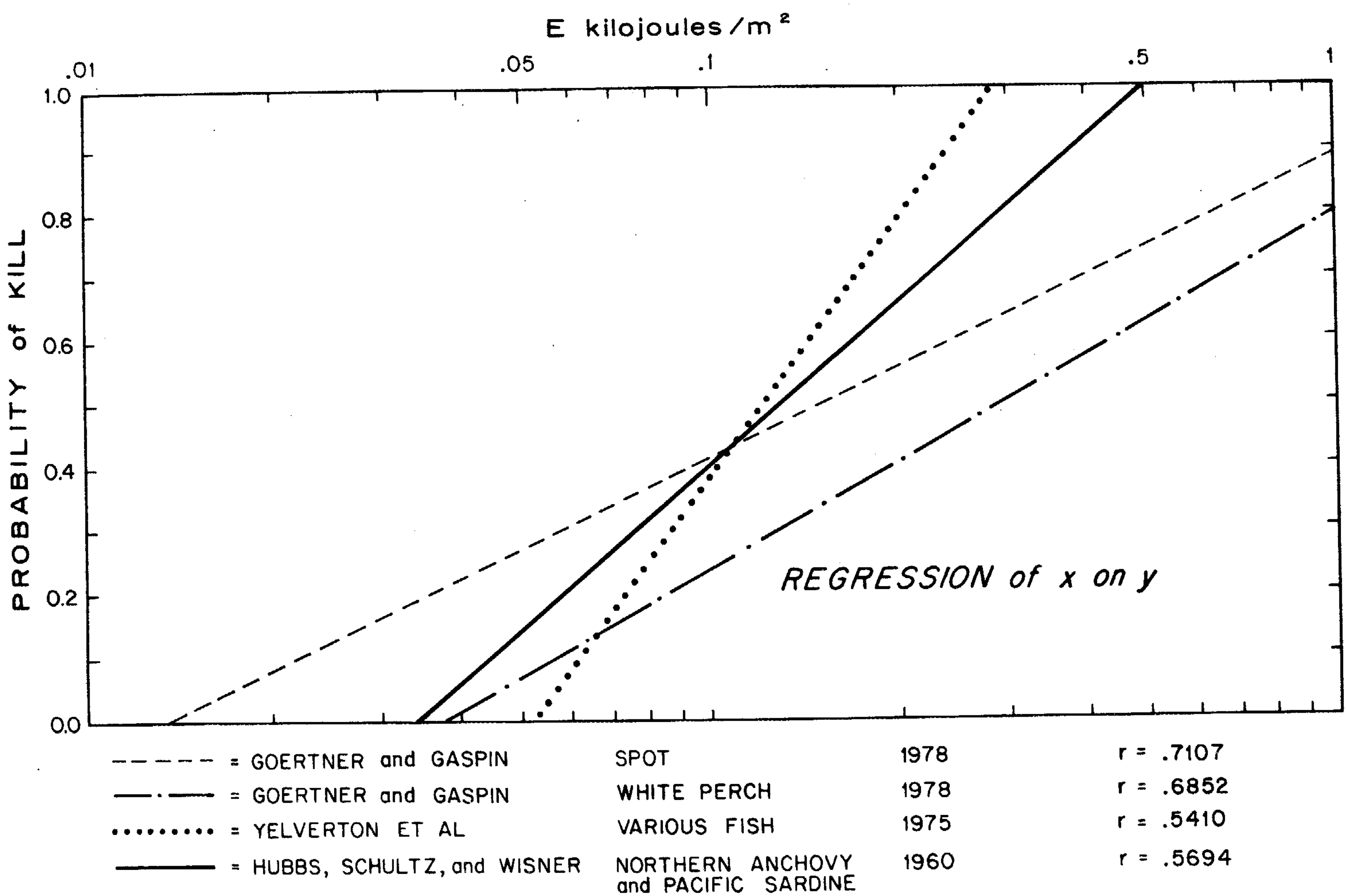

FIG. 4 Regression of log E on probability of kill.

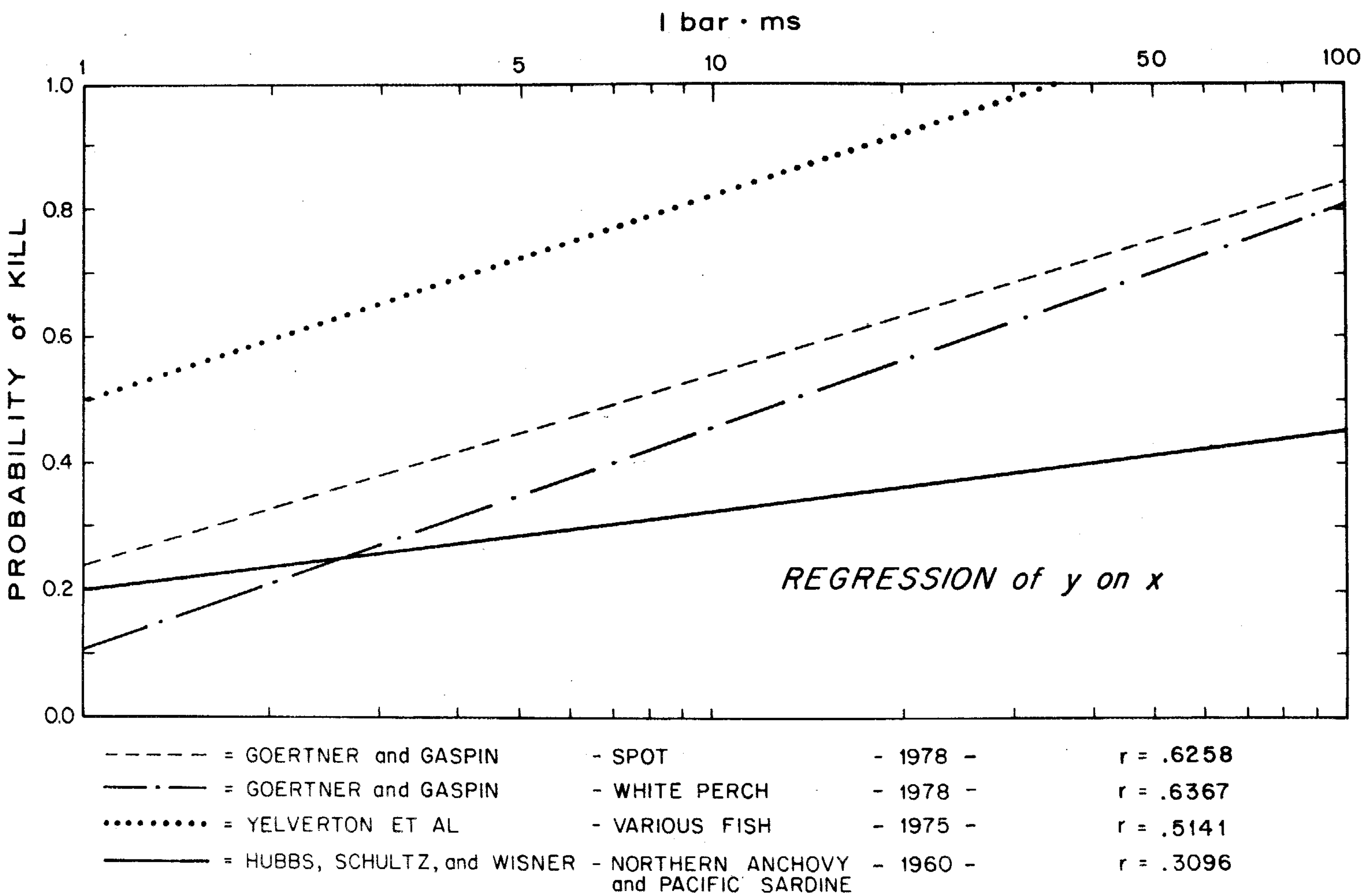

FIG. 5 Regression of probability of kill on log I.

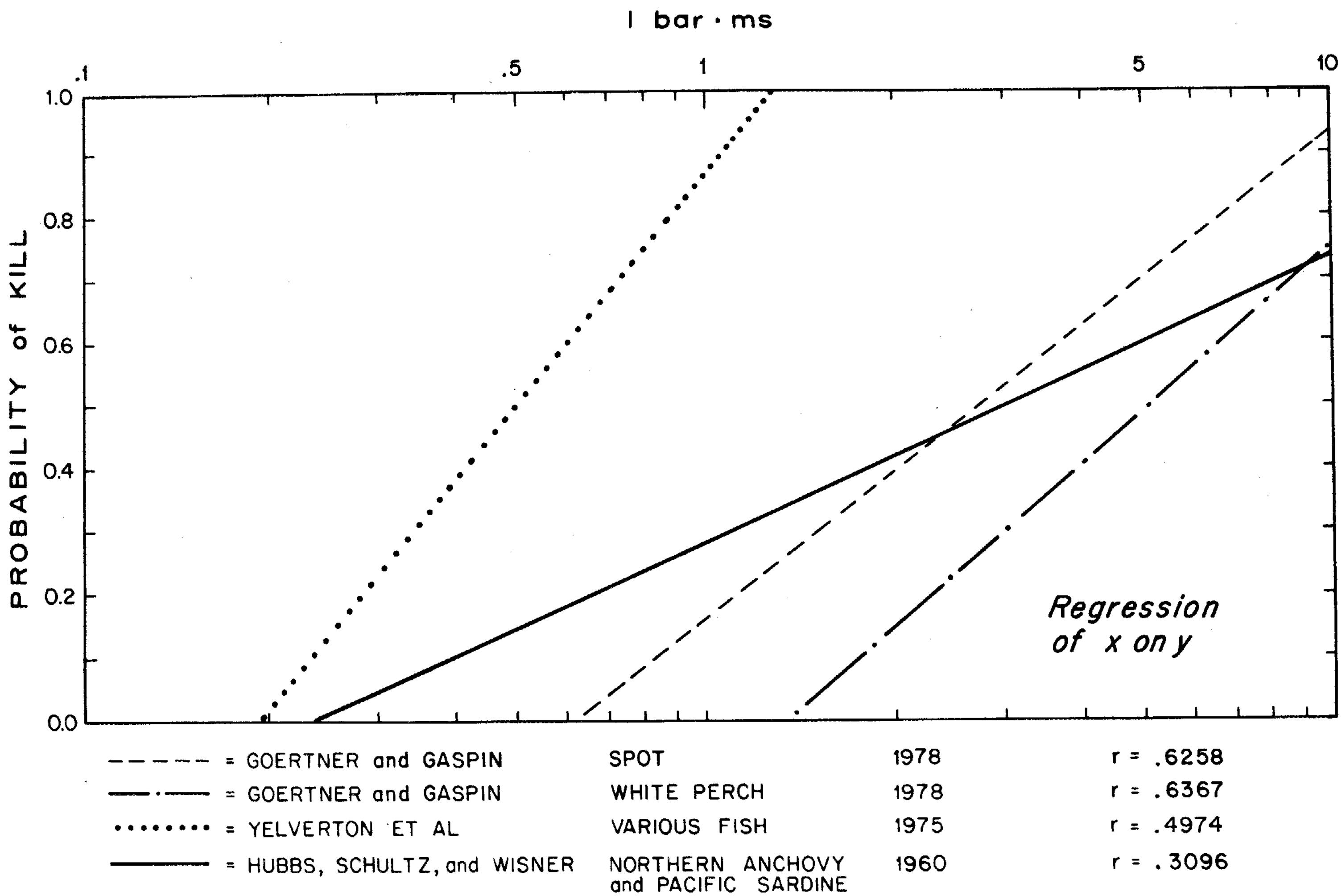

FIG. 6 Regression of log I on probability of kill (I = .1 to 10).

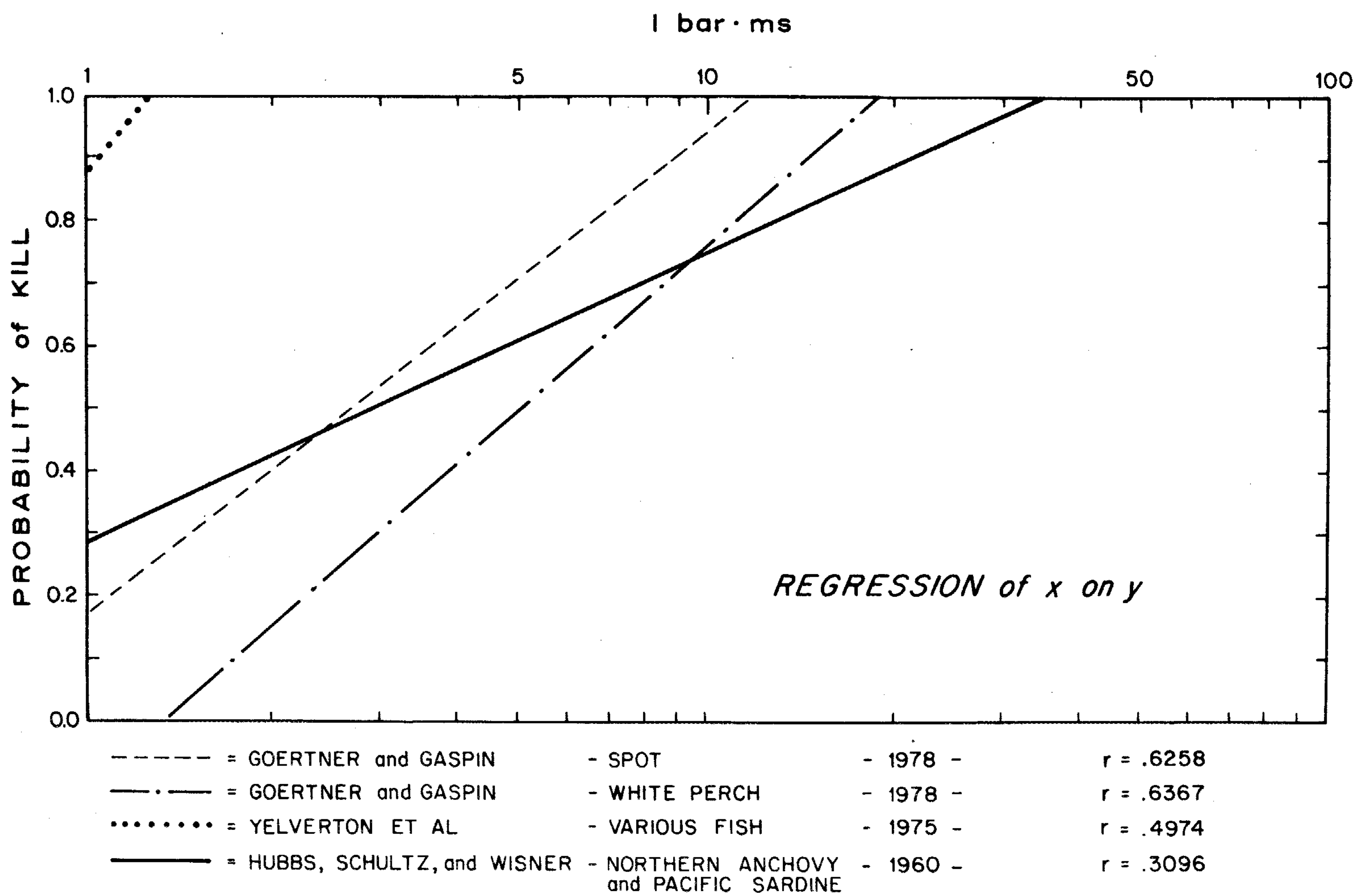

FIG. 7 Regression of log I on probability of kill (I = 1 to 100).

TABLE Ia

Regression of Probability of Kill on Parameter

Parameter	Data Set	Correlation	Intercept	Slope
	A	.588	- .0540	.173
	B	.604	- .222	.209
ln P_m	C	.543	- .484	.316
	D	.548	- .199	.204
	A	.626	.239	.131
	B	.637	.104	.152
ln I	C	.514	.497	.140
	D	.310	.201	.0548
	A	.711	- .141	.107
	B	.685	- .291	.116
ln E	C	.541	- .429	.174
	D	.569	- .304	.123

TABLE Ib

Regression of Parameter on Probability of Kill

Parameter	Data Set	Correlation	Intercept	Slope
	A	.588	- .695	.502
	B	.604	- 1.05	.571
$\ln P_m$	C	.543	- 2.52	1.07
	D	.548	- 1.11	.679
	A	.626	.168	.335
	B	.637	- .113	.376
$\ln I$	C	.514	.862	.529
	D	.310	.256	.572
	A	.711	- .558	.211
	B	.685	- .904	.247
$\ln E$	C	.541	- 2.35	.594
	D	.569	- 1.34	.379

b. Functions of fish depth, fish weight, carge depth, and charge weight

The above mentioned experiments by Yelverton et al., 1975, and analysis by Goertner (1978) have shown that probability of fish kill is related to fish depth, fish weight, charge depth and charge weight. At the depths tested, smaller fish appear to be more vulnerable than larger fish. At the surface the over-pressure from the charge is released by the interface and fish are protected. For a given charge depth and for fish of a given size there is a shallow depth of submergence at which fish are most vulnerable because the time interval between the direct arrival and the surface reflection matches the resonant period of their swim bladders. This depth of maximum vulnerability is greater for large fish. At depths greater than the d.m.v., the ratio of the over-pressure to the ambient pressure is less and the fish are not so severely affected.

The elements not included in the preceeding section are ambient pressure, P_a, and fish weight, W_f. An increase in either has a tendency to decrease vulnerability. Therefore, damage parameters constructed with the reciprocals of these elements or some power of such reciprocals could yield higher correlation coefficients. In analyzing the Yelverton and Gaspin data, Goertner (1978) has shown that the factor for fish weight is $1/W_f^{1/3}$.

The theory presented in the Goertner paper relates the damage to swim bladder fish to excitation of the swim bladder as an oscillating bubble of gas. Goertner's damage parameter is the ratio of maximum to minimum radius of an oscillating spherical bubble excited by the blast and its surface reflections. The rest volume of Goertner's spherical bubble was adjusted for fish species and size to maximize the correlation between the calculated motion and observed injuries in the experiments of Gaspin, 1975, and Gaspin et al., 1976. The calculations outlined by Goertner are somewhat more laborious than the damage parameters we discuss. While we believe that the Goertner theory is essentially correct, the spread of the data is such that the correlations obtained by Goertner are not significantly different from those that we obtain below from the damage parameters log $(I/P_a W_f^{1/3})$ or log $(E/P_a W_f^{1/3})$. The correlations that we obtain for these parameters however, (Figures 8-11, and Table II) are higher than those obtained for Section IIIa. This supports what we have said about the effects of fish weight and ambient pressure.

Kenard (1943) has shown that the period of oscillation of a bubble at small amplitude is proportional to its radius divided by the square root of the ambient pressure. The radius of an equivalent bubble is proportional to the cube root of its volume or to $W_f^{1/3}$. Therefore, in this context time has dimensions $W_f^{1/3}/P_a^{1/2}$. The impulse I has dimensions $P_o.t$ and in $I/P_a^{1/2} W_f^{1/3}$ the dimensions cancel Similarly the dimensions cancel in $E/P_a^{3/2} W_f^{1/3}$ because E has dimension $P^2.t$. These considerations suggest that the parameters log $(I/P_a^{1/2} W_f^{1/3})$ and log $(E/P_a^{3/2} W_f^{1/3})$ be tried (Figures 12-15). If the protective effect of pressure follows these relations one would expect higher correlation coefficients for data set D which covers a much larger spread in ambient pressure than the other data.

TABLE IIa

Regression of Probability of Kill on Parameter

Parameter	Data Set	Correlation	Intercept	Slope
	A	.742	.361	.167
	B	.772	.457	.222
$\ln\ (I/P_a W_f^{1/3})$	C	.789	.976	.355
	D	.569	.401	.128
	A	.776	-.0954	.120
	B	.748	-.131	.137
$\ln\ (E/P_a W_f^{1/3})$	C	.575	-.443	.213
	D	.611	-.0843	.109
	A	.698	.326	.150
	B	.690	.362	.176
$\ln\ (I/P_a^{1/2} W_f^{1/3})$	C	.792	.940	.353
	D	.439	.299	.0902
	A	.777	-.0569	.117
	B	.769	-.111	.146
$\ln\ (E/P_a^{3/2} W_f^{1/3})$	C	.548	-.368	.198
	D	.583	.00651	.0894

TABLE IIb

Regression of Parameter on Probability of Kill

Parameter	Data Set	Correlation	Intercept	Slope
	A	.742	.424	.304
	B	.772	.596	.373
$\ln\ (I/P_a W_f^{1/3})$	C	.789	1.34	.570
	D	.569	.831	.396
	A	.776	- .347	.198
	B	.748	- .433	.246
$\ln\ (E/P_a W_f^{1/3})$	C	.575	- 2.08	.644
	D	.611	- .544	.293
	A	.698	.371	.315
	B	.690	.483	.370
$\ln\ (I/P_a^{1/2} W_f^{1/3})$	C	.792	1.28	.562
	D	.439	.736	.468
	A	.777	- .281	.193
	B	.769	- .362	.247
$\ln\ (E/P_a^{3/2} W_f^{1/3})$	C	.548	- 2.07	.657
	D	.583	- .359	.263

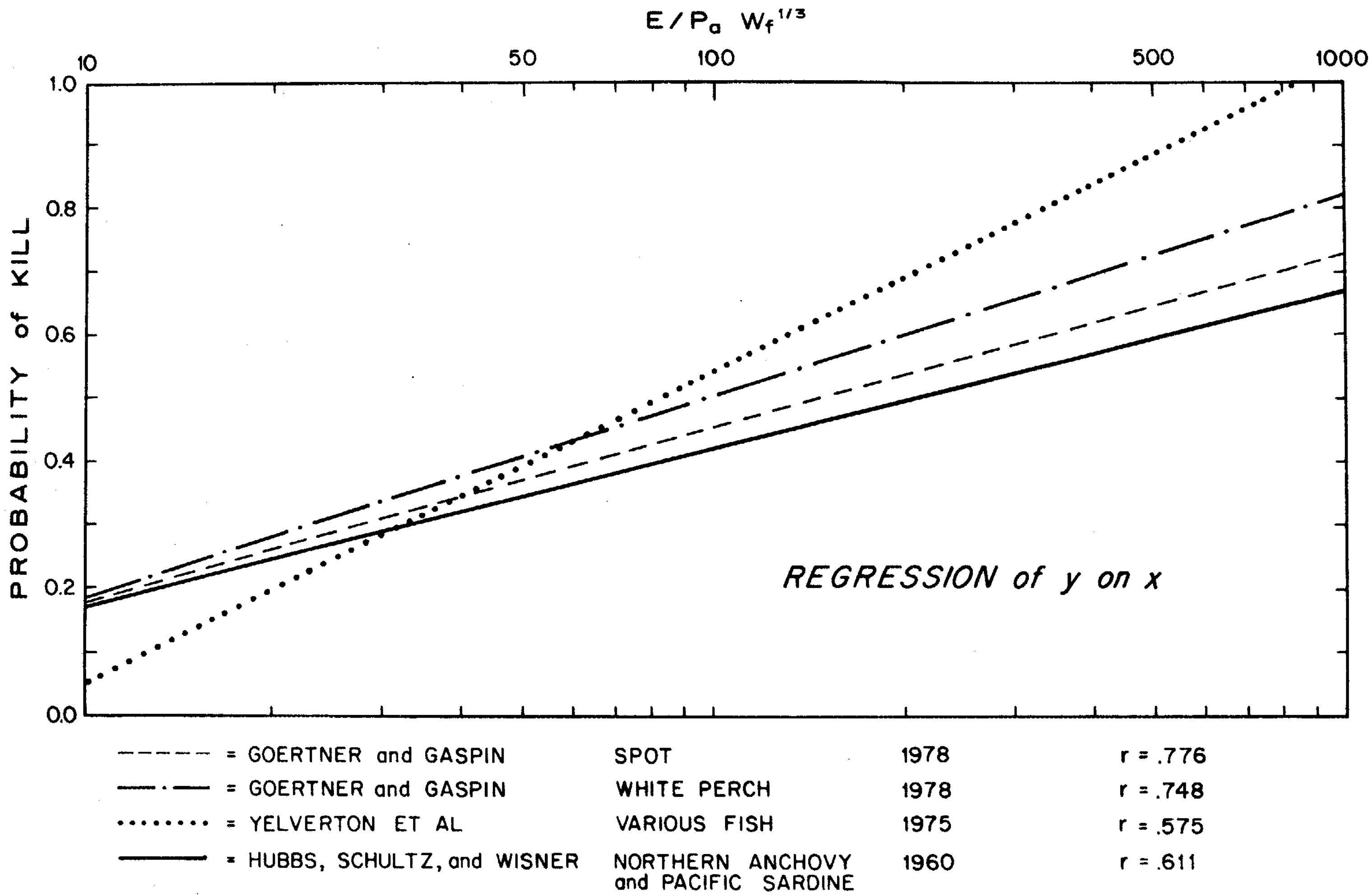

FIG. 8 Regression of probability of kill on log $(E/P_a W_f^{1/3})$.

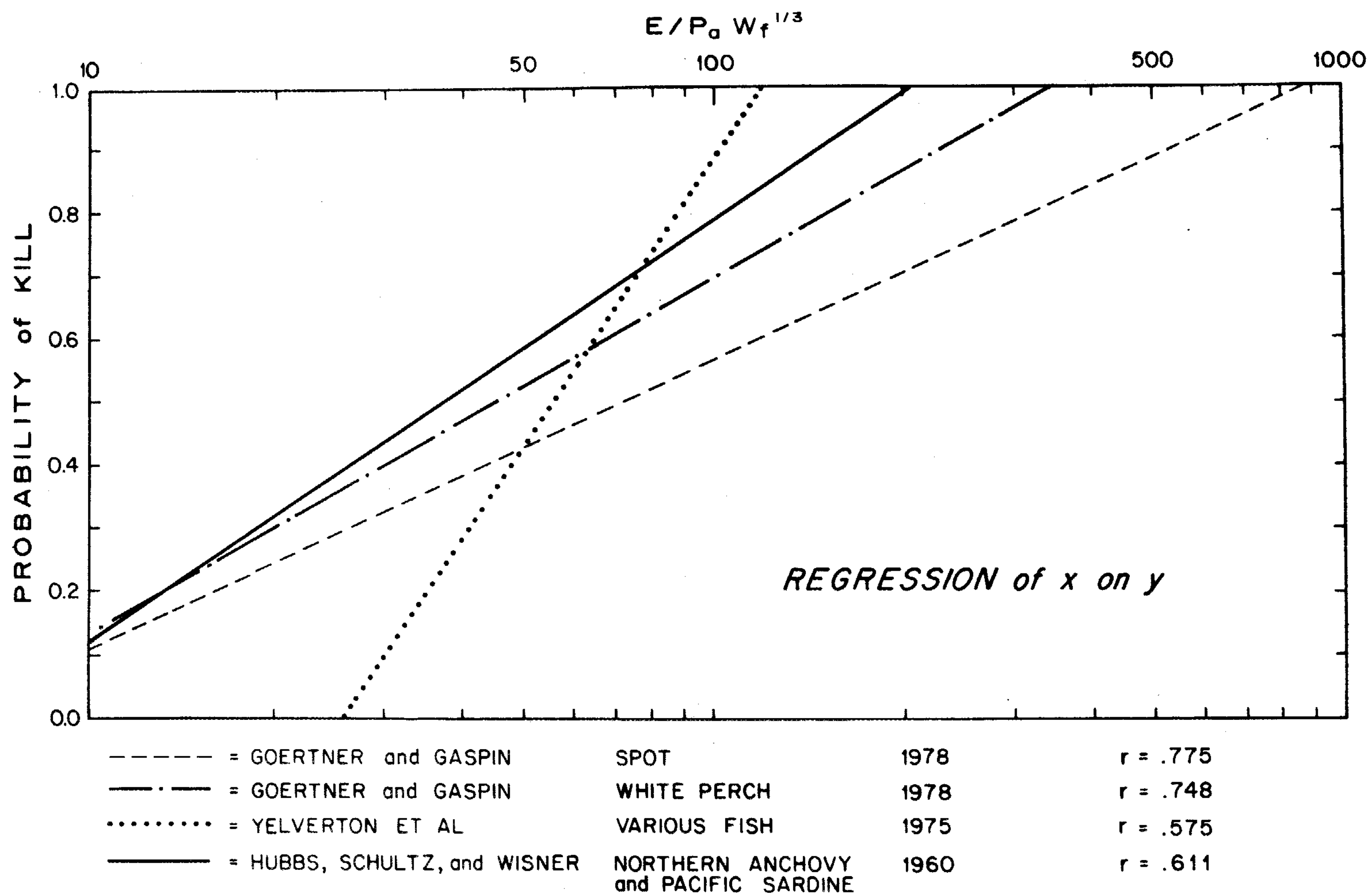

FIG. 9 Regression of log $(E/P_a W_f^{1/3})$ on probability of kill.

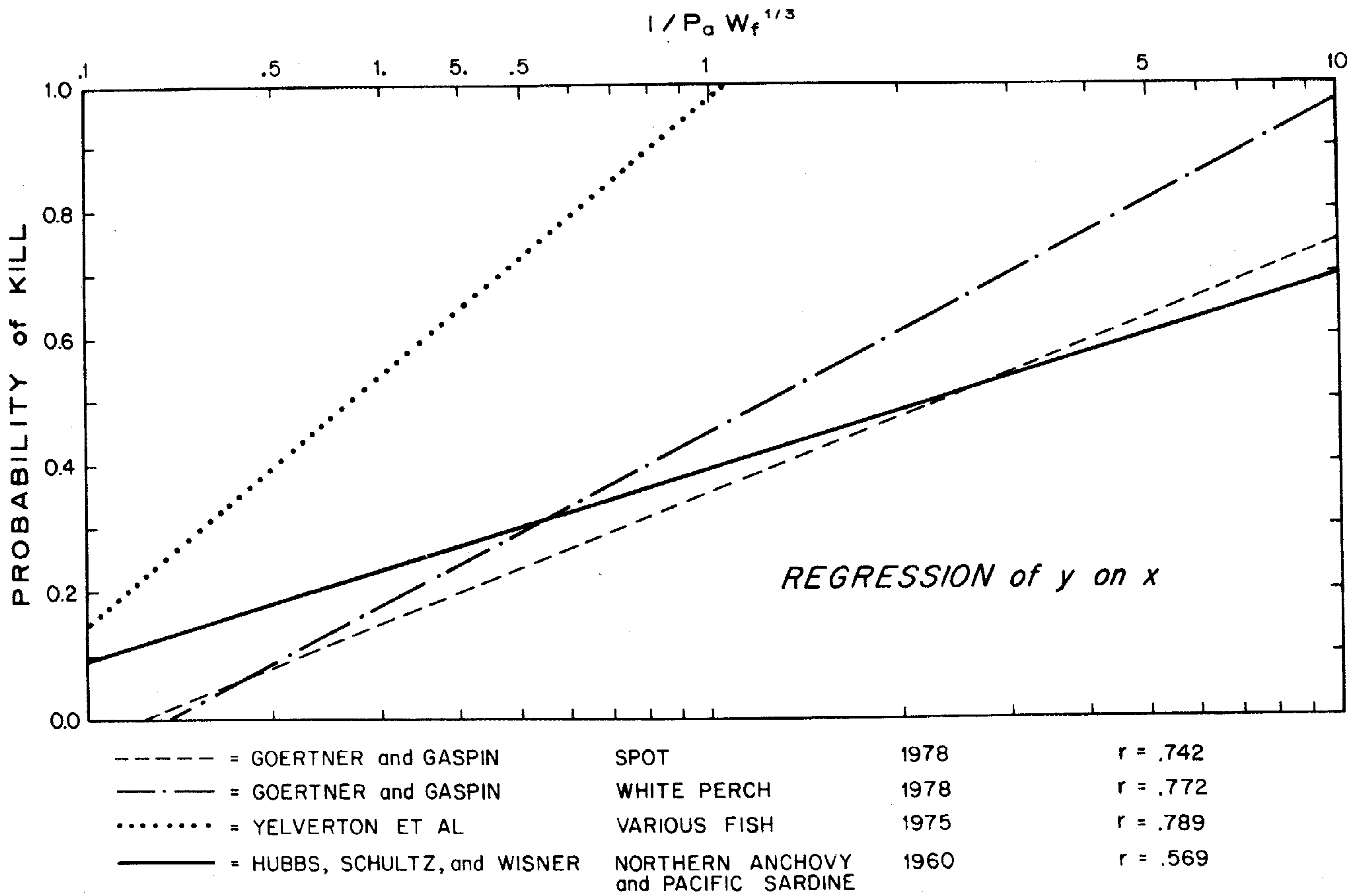

FIG. 10 Regression of probability of kill on log $(I/P_a W_f^{1/3})$.

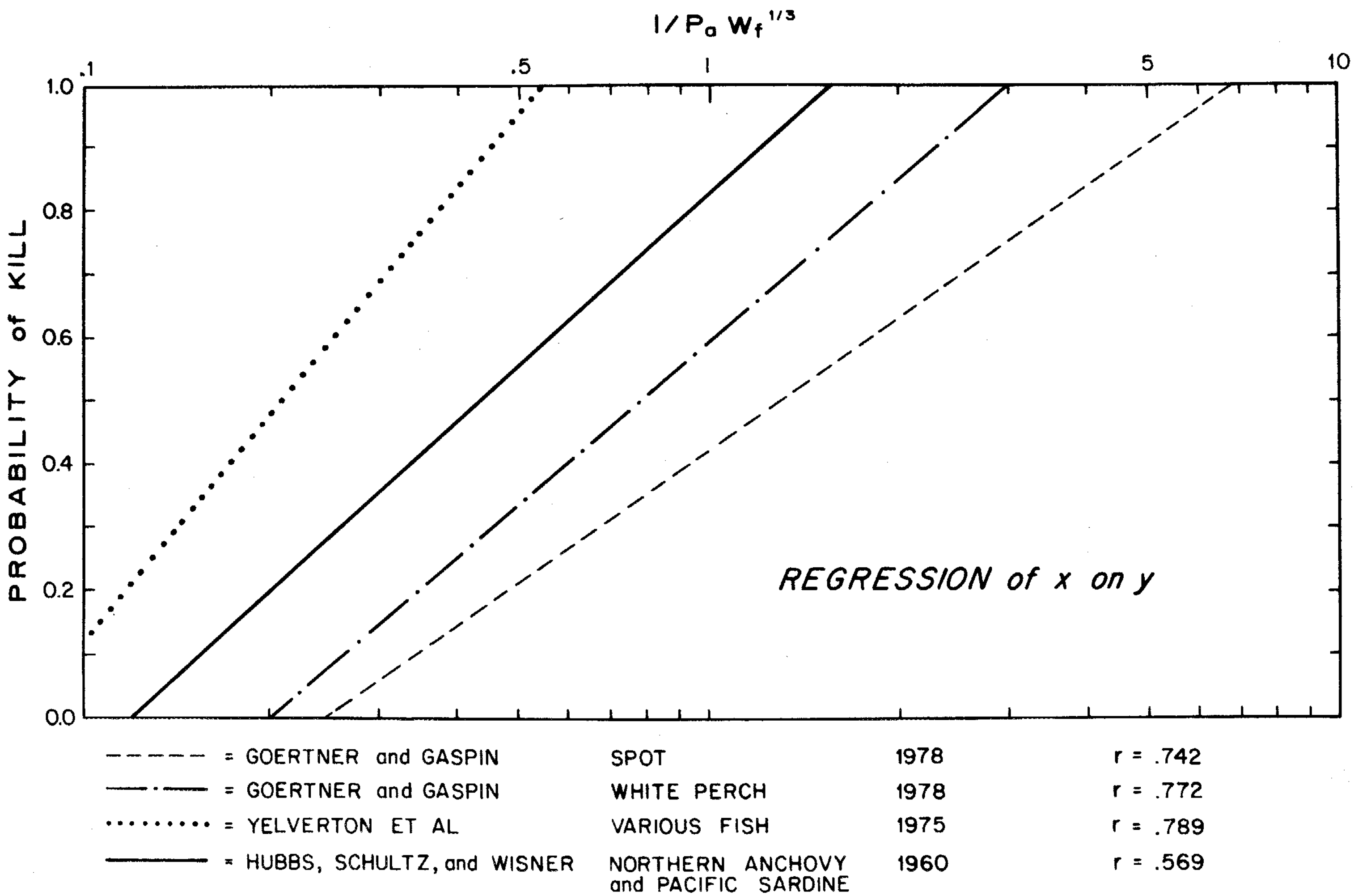

FIG. 11 Regression of log $(I/P_a W_f^{1/3})$ on probability of kill.

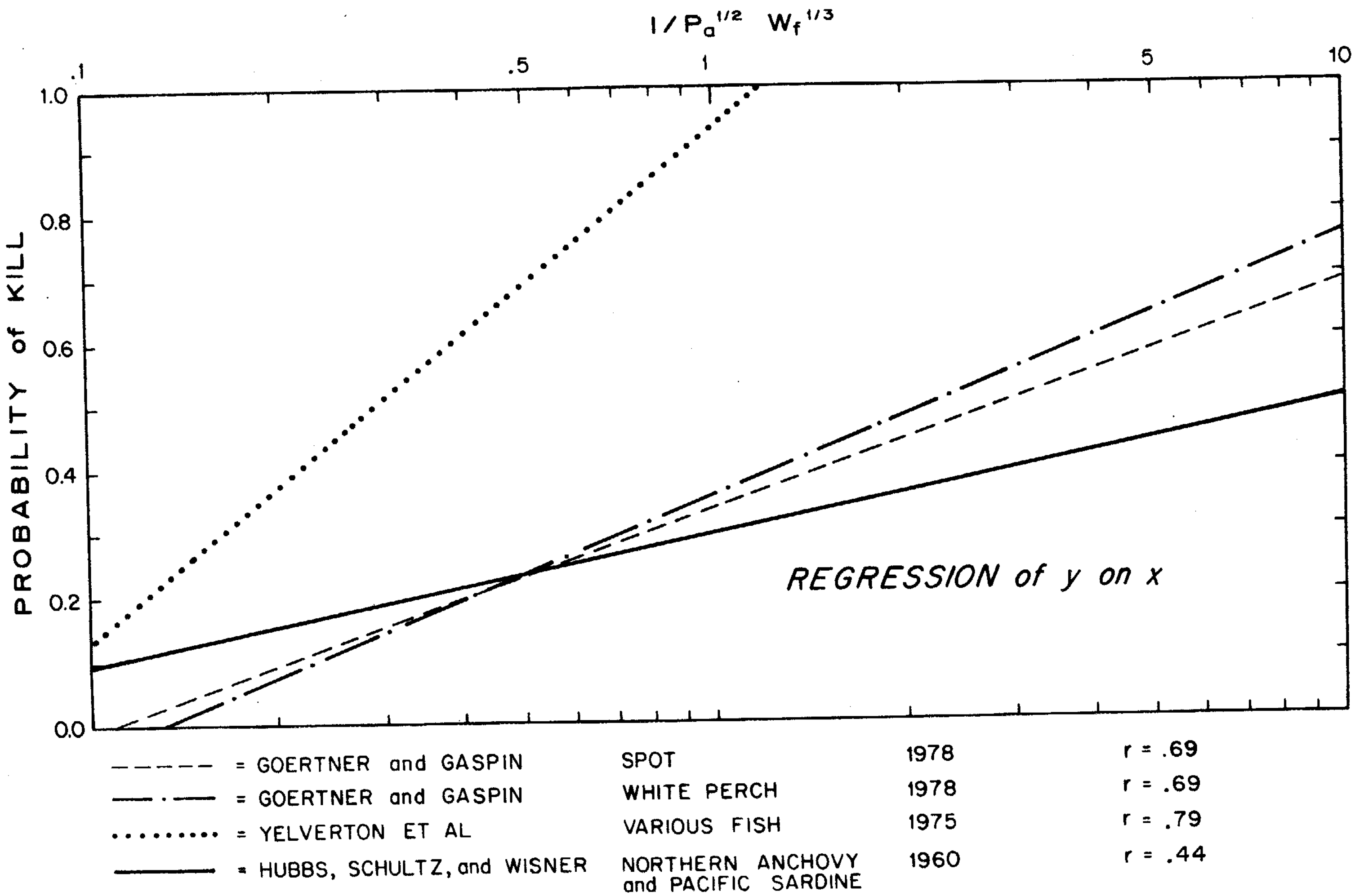

FIG. 12 Regression of probability of kill on log $(I/P_a^{1/2}W_f^{1/3})$.

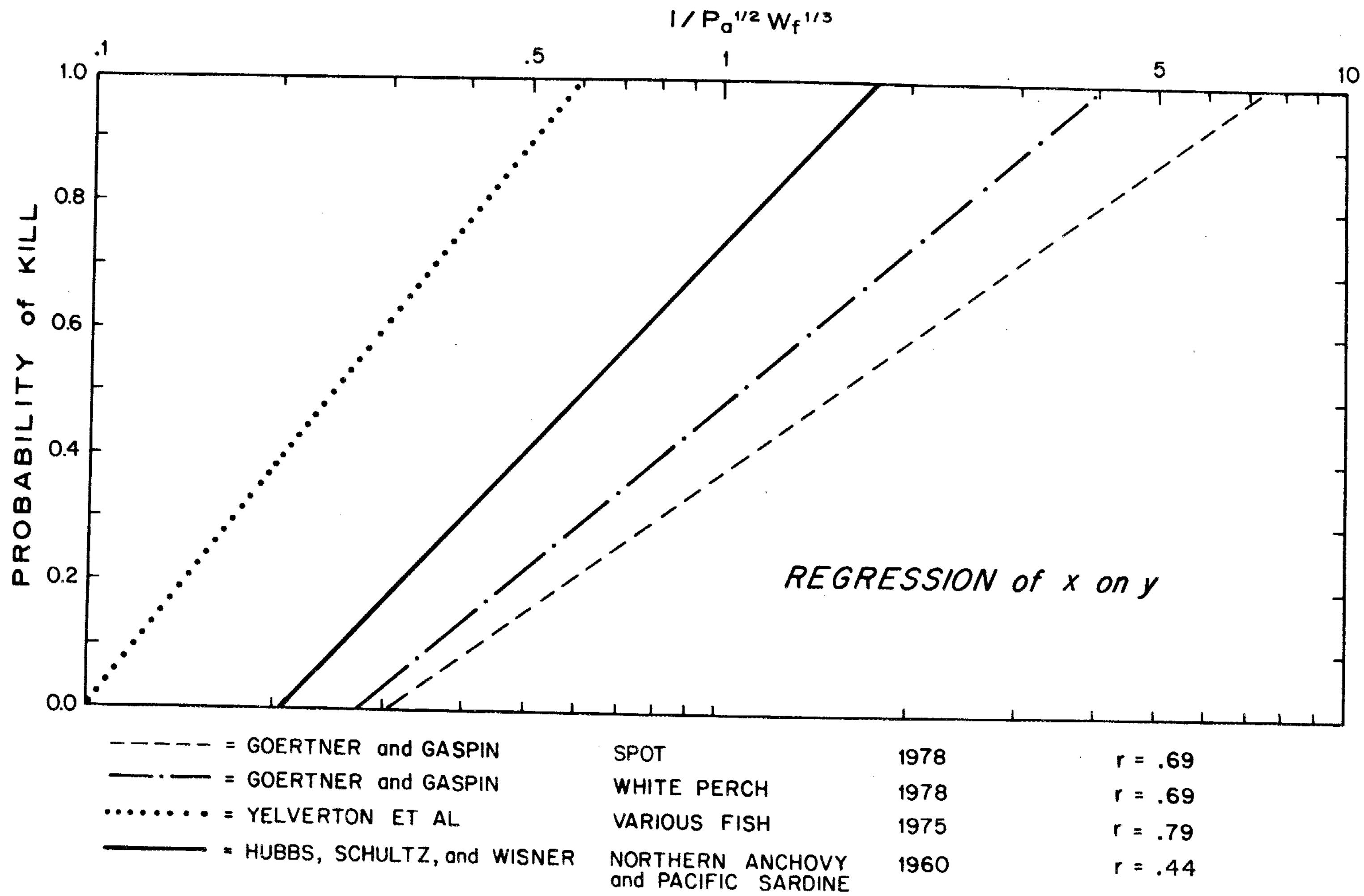

FIG. 13 Regression of log $(I/P_a^{1/2} W_f^{1/3})$ on probability of kill.

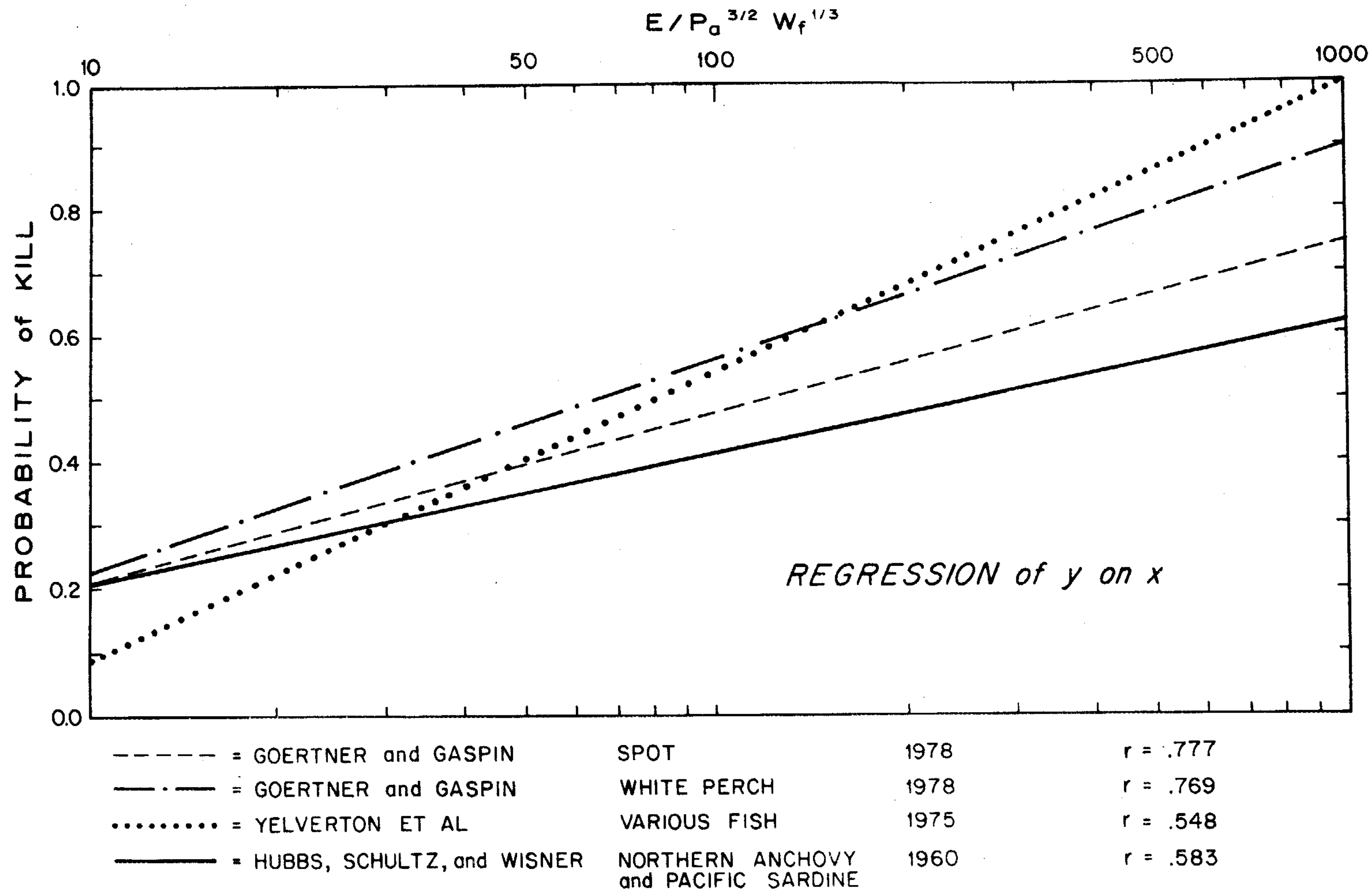

FIG. 14 Regression of probability of kill on log $(E/P_a^{3/2}W_f^{1/3})$.

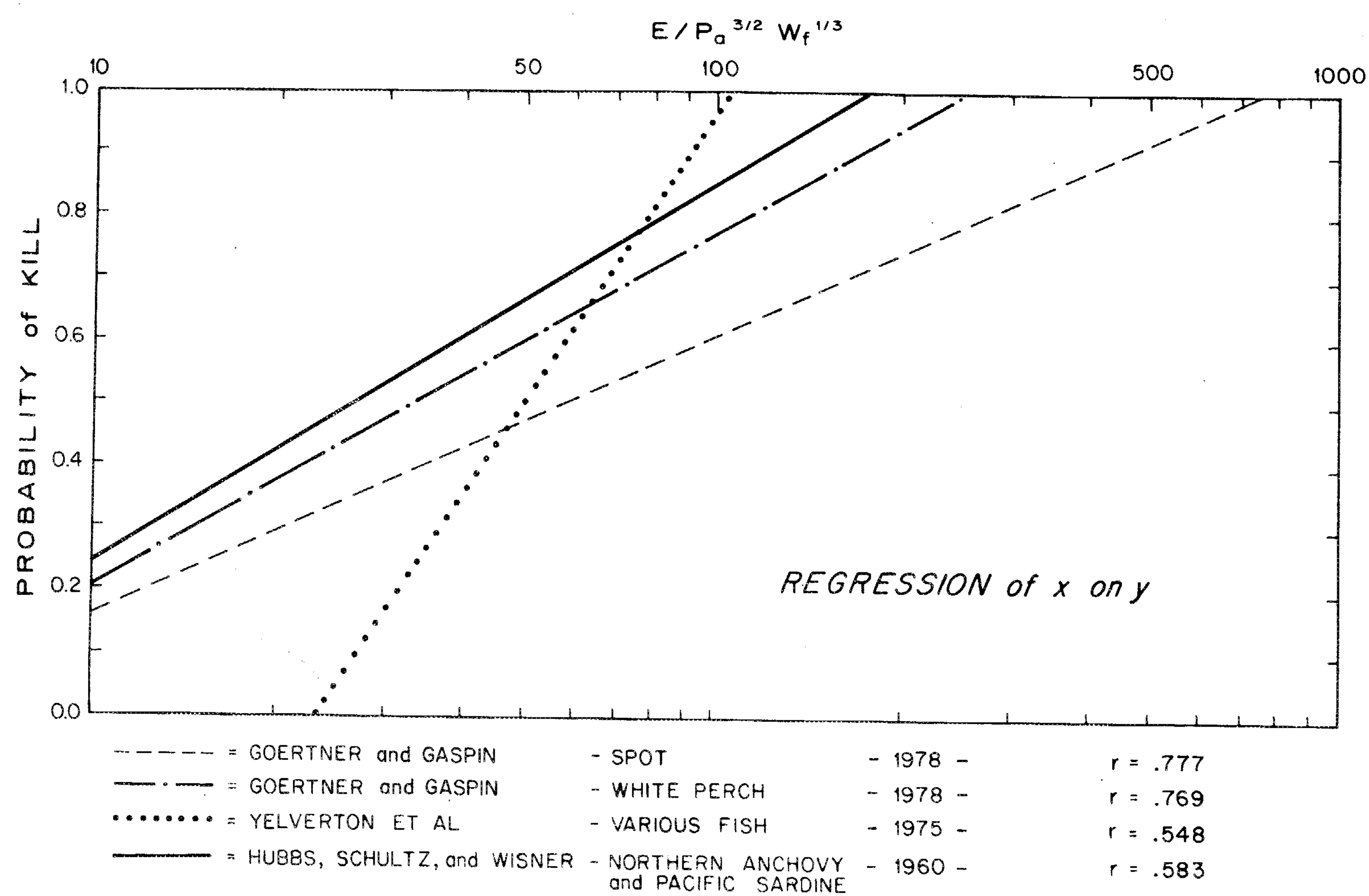

FIG. 15 Regression of log ($E/P_a^{3/2}W_f^{1/3}$) on probability of kill.

The correlation is actually lower; this suggests that it is better to consider the protective effect of pressure as a first power relation as we have done in Figures 8 to 11.

IV CALCULATIONS OF DAMAGE PARAMETERS:

To evaluate the damage parameters for the various experiments that we have analyzed statistically, we have used the empirical relations based on physical measurements and on the Principle of Similarity (Cole, 1948). These relationships may be summarized as follows:

$$Q = W^{1/3}/R$$
$$P_m = k\,(Q)^{\alpha}$$
$$I = l\,R\,(Q)^{(\beta + 1)}$$
$$E = m\,R\,(Q)^{(\phi + 1)}$$
$$t_o = n\,R\,(Q)^{(\theta + 1)}$$

where k, l, m, n, α, β, ϕ, θ are constants and

W = weight of charge (kg)

R = range (meters)

P_m = maximum blast pressure (bars)

I = impulse (bar.msec)

E = energy flux (Joules/m^2)

t_o = time constant of initial explosion pulse (μ sec)

For TNT, Hill (1978) gives the following values:

k = 524	α = 1.13
l = 57.5	β = 0.89
m = 82100	ϕ = 2.05
n = 92.5	θ = 0.22

Constants for other detonating explosives such as tetryl, pentolite, nitromethane, and dynamite are not very different.

The quantities calculated by the above formulas are for spherical charges in water far from surface or bottom boundaries and where the quantities are measured at distances between seven charge radii and 900 charge radii. Hill states that these limits for a 2.5 kg charge of TNT would correspond to .5 meters to 64 meters. If bottom reflections or multiple paths are not important, the approximations are fairly good well beyond the upper limit.

Since the water surface is a pressure release boundary, the reflected wave terminates the pressure pulse at shallow depths. According to Yelverton et al., 1975 the impulse including the effect of surface reflection may be calculated by the following formulas:

$$I = P_m \cdot t_o \left[\frac{9}{11} \cdot \left(1 - e^{\frac{11t_c}{10t_o}}\right) + 1 - e^{\frac{-t_c}{10t_o}}\right]$$

where t_c is the time to surface cut-off and

$$t_c = \left(\sqrt{R^2 + 4\,D_cD_f} - R\right) / C_o$$

where

D_c = depth of charge
D_f = depth of fish
R = slant range
C_o = speed of sound in water
e = 2.7183

Yelverton et al., 1975 give curves which may be used to calculate impulse for given charge weight and geometry. Hill (1978) reproduces these curves in the units we use. The version of the curves from the Hill paper are reproduced here as Figure 16. To calculate I using these curves, first calculate $A = D_c x D_f / W^{2/3}$ and $R/W^{1/3}$. Find the point where the curve for the value of A has the ordinate $R/W^{1/3}$. The abscissa of that point multiplied by $W^{1/3}$ is the required value of I.

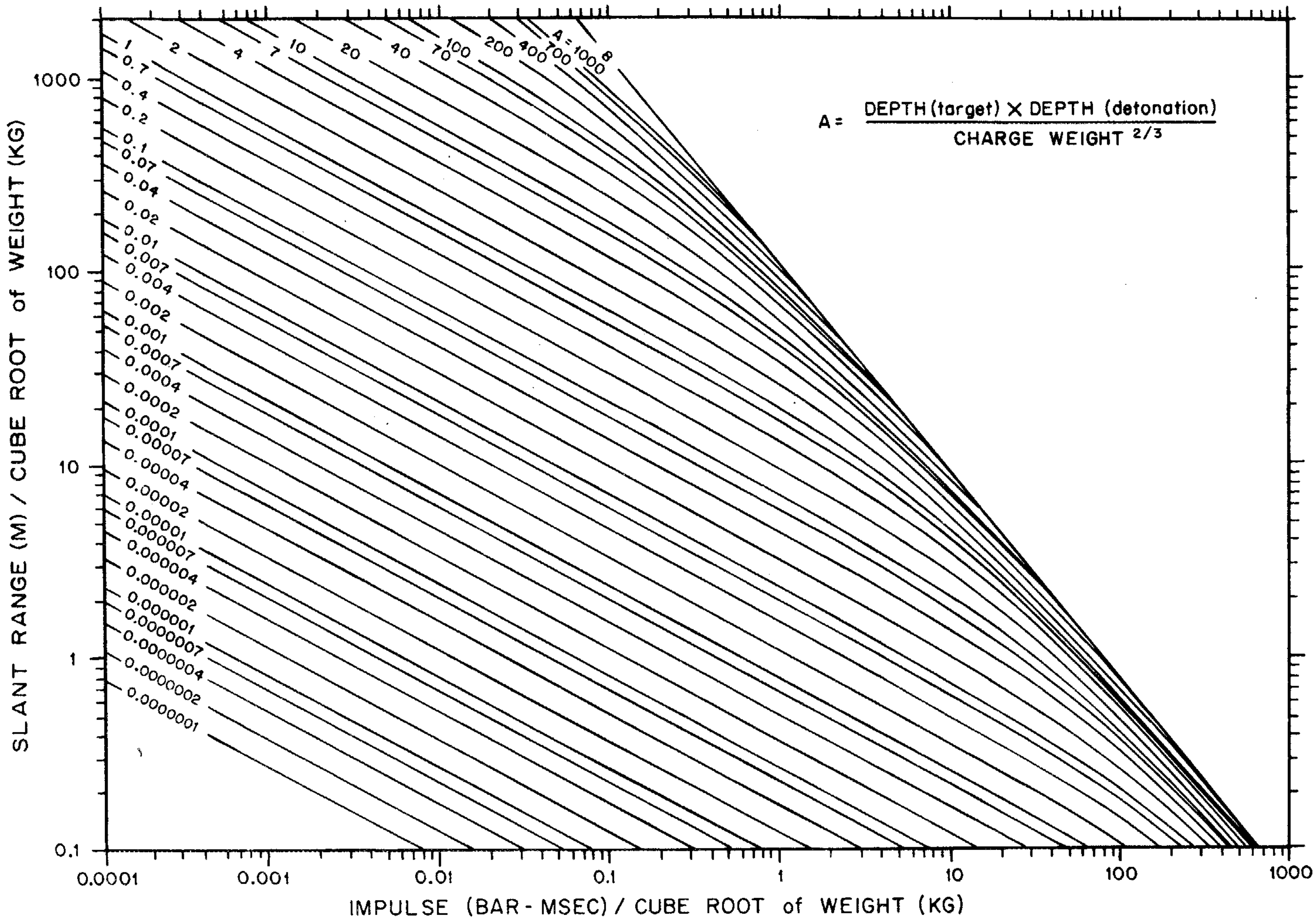

FIG. 16 Curves for calculaing impulse after Yelverton et al (1975) as redrawn by Hill (1978) for metric units.

To include surface reflection in the calculation of E with any accuracy would require more information than is available. Therefore, we used the simple free field formula. For this reason the correlation of the E-based parameters for the Yelverton data which was all shallow may be expected to be low. If one is especially interested in damage to fish swimming near the surface, the I-based parameters are more reliable.

Calculation of the parameters for a well-severance explosion or for many experiments cannot be done accurately from these formulae because the simple conditions of a bare spherical charge in water far from boundaries are violated. The effects of charge burial in the bottom and containment in the well casing are difficult to calculate. Experimental measurements are needed. For a charge buried in solid sediment the bubble pulse is eliminated or greatly modified (Weston, 1960A).

Hubbs and Rechnitzer (1952) performed an experiment with fish in cages and shots jetted into the bottom. The depth below the bottom of their buried charges varied from about one to about 17 meters. They measured peak pressures and calculated a decrease varying with the 2.6 power of the distance. This is a much greater attenuation than the 1.13 power found in water. They found, however, that buried charges still killed fish. In examining their data we confirmed their attenuation coefficient of 2.6, but found that the measured peak levels could be matched only if the peak pressure at the charge was about seven times that of an equivalent charge in water. That is, for a buried charge, the peak pressure starts out higher, but is attenuated more rapidly. If peak pressure is the parameter, the charge must be buried fairly deeply before greater attenuation in sediment overpowers the tamping effect that increases the peak pressure at the source. Without more data we cannot say what the effect on the other parameters might be.

V. CONTOURS OF KILL PROBABILITY:

Choosing the E-based parameter, log $(E/P_a\ W_f^{1/3})$, which may be more reliable for most of the water column, we have calculated contours of kill probability vs. range and depth for several different fish weights. The 11.3 kg charge is assumed to be on the bottom at a depth of 100 meters. No allowance has been made for possible attenuation by the well-casing and sediment, which might reduce the kill probabilities or for tamping effects which might increase the effective source peak pressure and increase kill probabilities. Since smaller fish are more vulnerable, Figure 17 for 100 gm fish gives the largest kill volume. If the volumes enclosed by the contours are weighted by the kill probabilities and added, we get a kill volume of about 1.6×10^5 cubic meters. The kill volume for a mixed assortment of fish would be more difficult to calculate, but would probably be smaller unless most of the fish were lighter than 100 gms. Figures 18 through 20 show the contours for 500-gm, 2.5 kg, and 12.5 kg fish.

VI. PROBABLE CONCENTRATION OF FISH AT OIL RIG LOCATIONS ON GEORGES BANK:

a. Surveys and Other Data

Table III gives total tonnage of fish in various categories caught on Georges Bank in the years 1977, 1978, 1979 and 1980. These data have been abstracted from a report of the Northwest Atlantic Fisheries

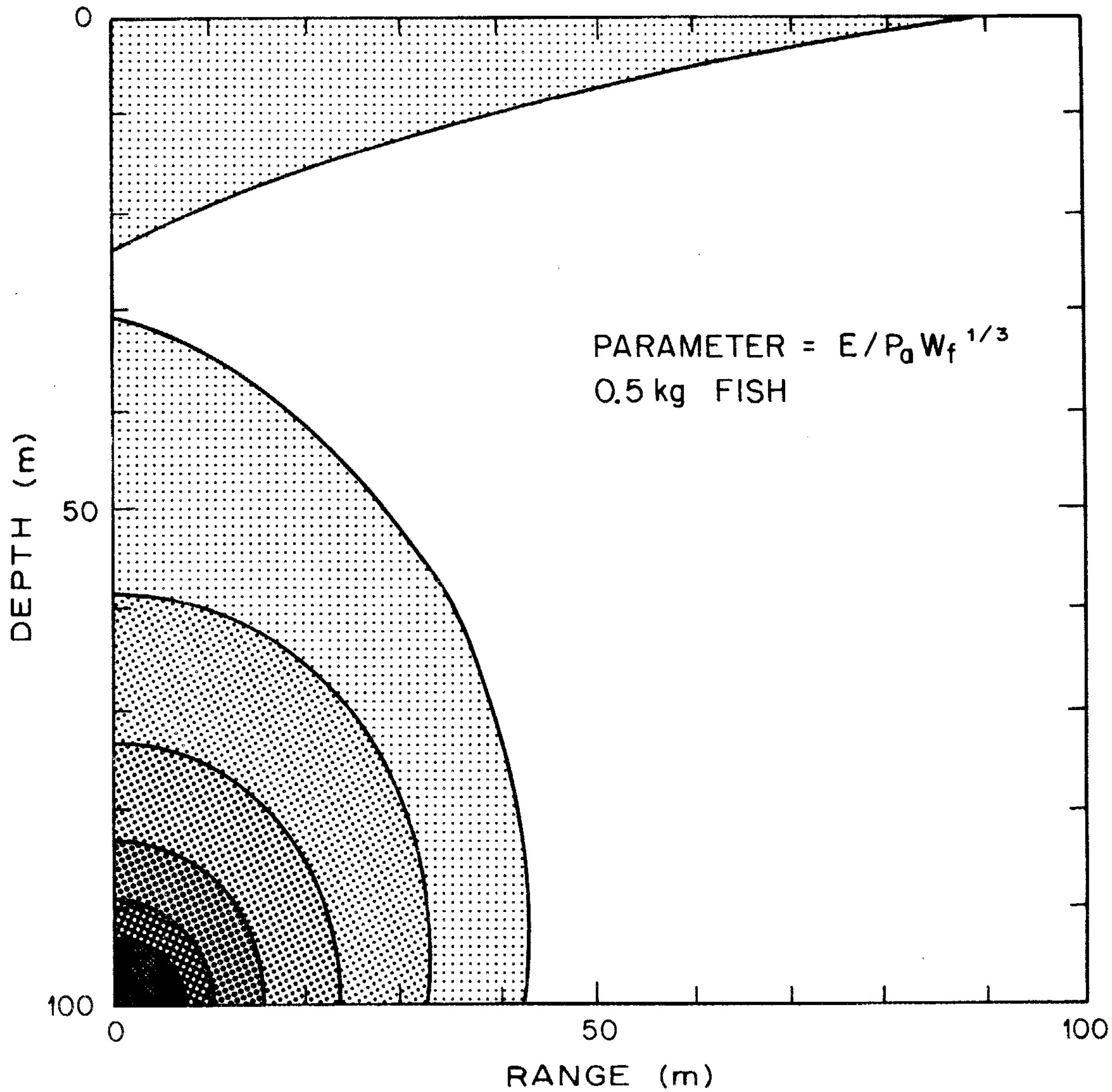

FIG. 18 Contours of kill probability vs. range & depth for 500 gm fish and 11.3 kg charge at 100 meters depth assuming $\log (E/P_a W_f^{1/3})$ as parameter. Note on pressure release (see Fig. 17) also applies to this figure.

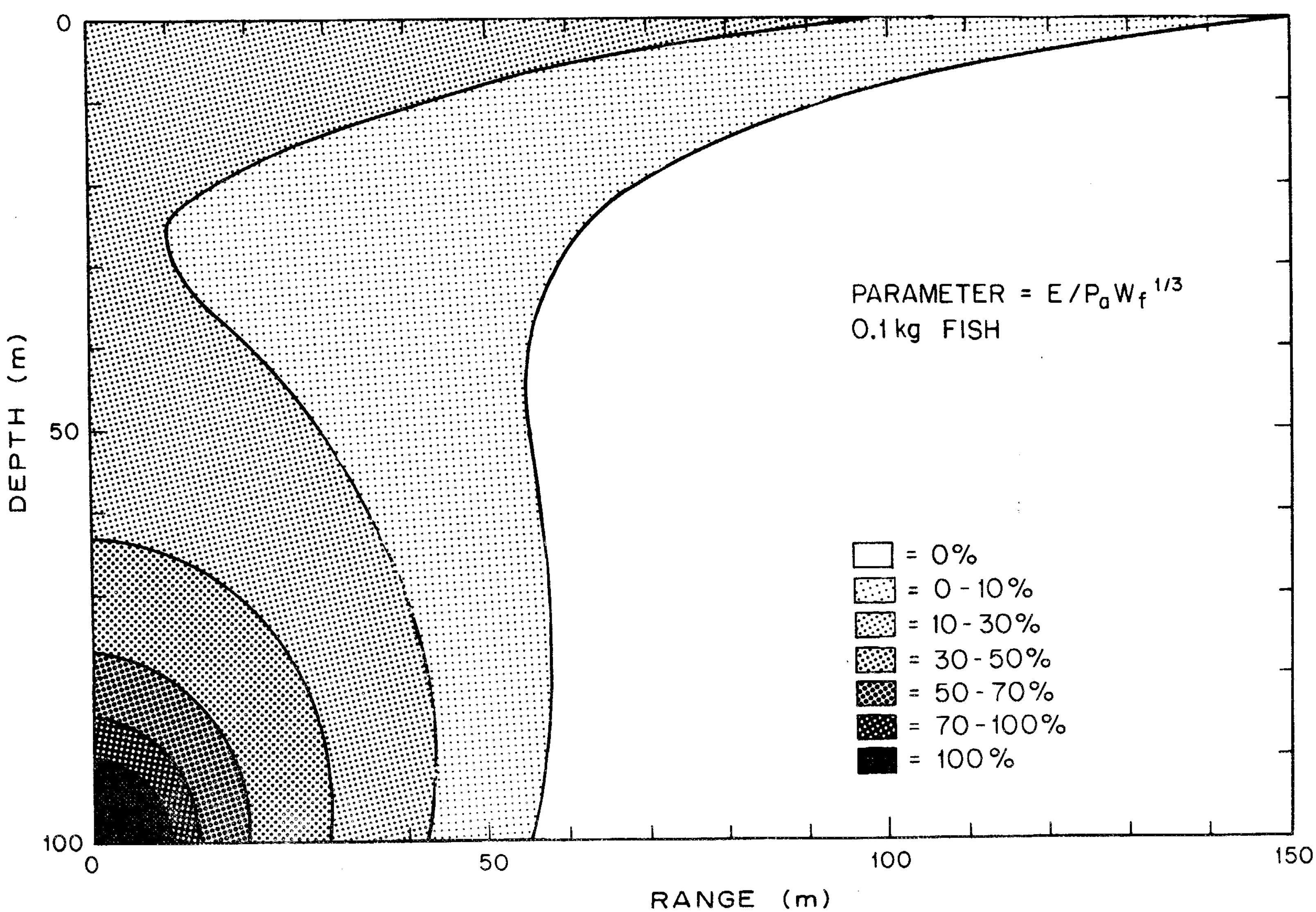

FIG. 17 Contours of kill probability vs. range & depth for 100 gm fish and 11.3 kg charge at 100 meters depth assuming log $(E/P_a W^{1/3})$ as parameter. Protection by pressure release at water surface not accounted for by this model would reduce probability of kill for 0-5 meters depth below that shown here.

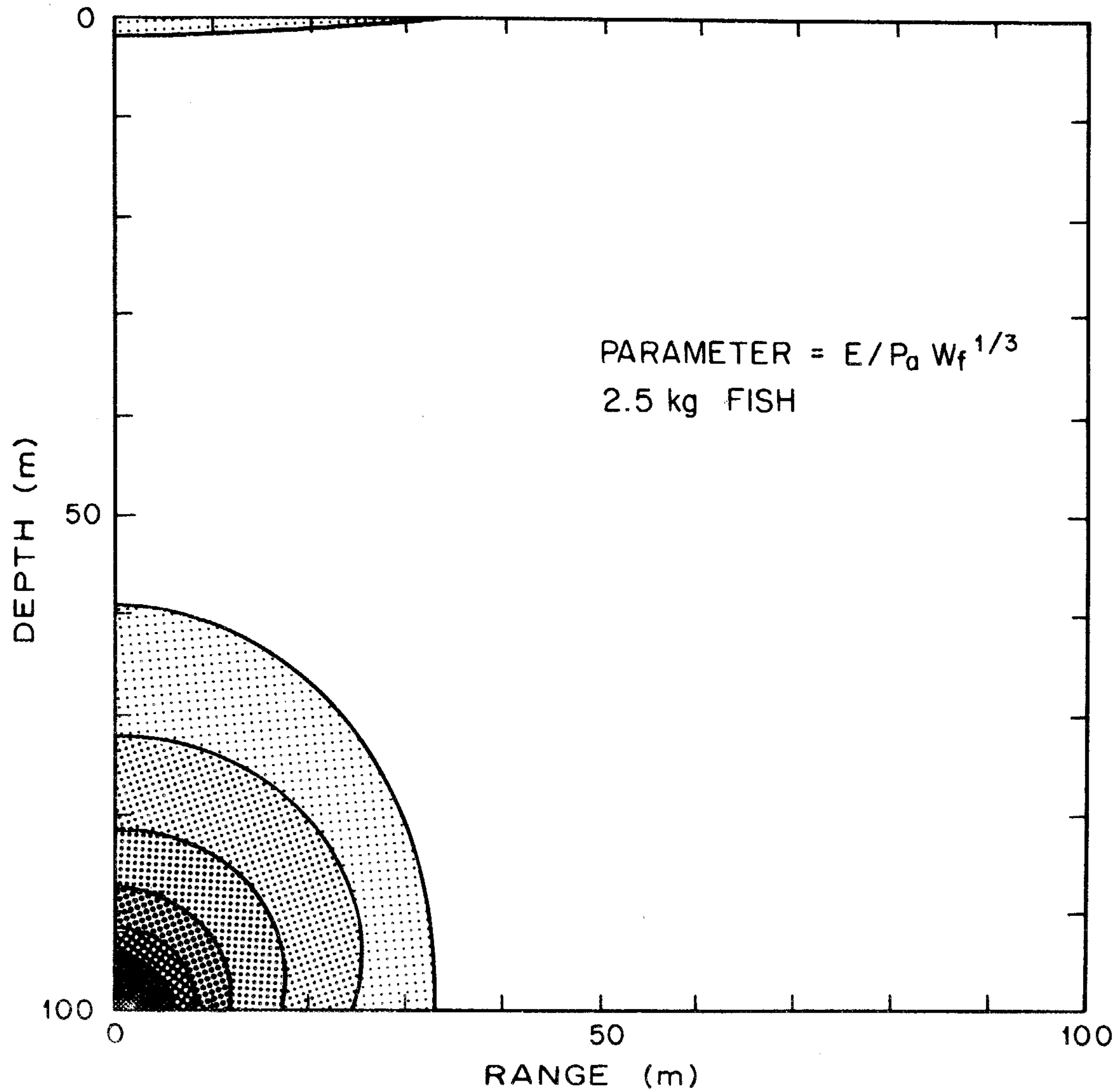

FIG. 19 Contours of kill probability vs. range and depth for 2.5 kg. fish and 11.3 kg. charge at 100 meters depth assuming log $(E/P_a W_f^{1/3})$ as parameter. Note on pressure release (see Fig. 17) also applies to this figure.

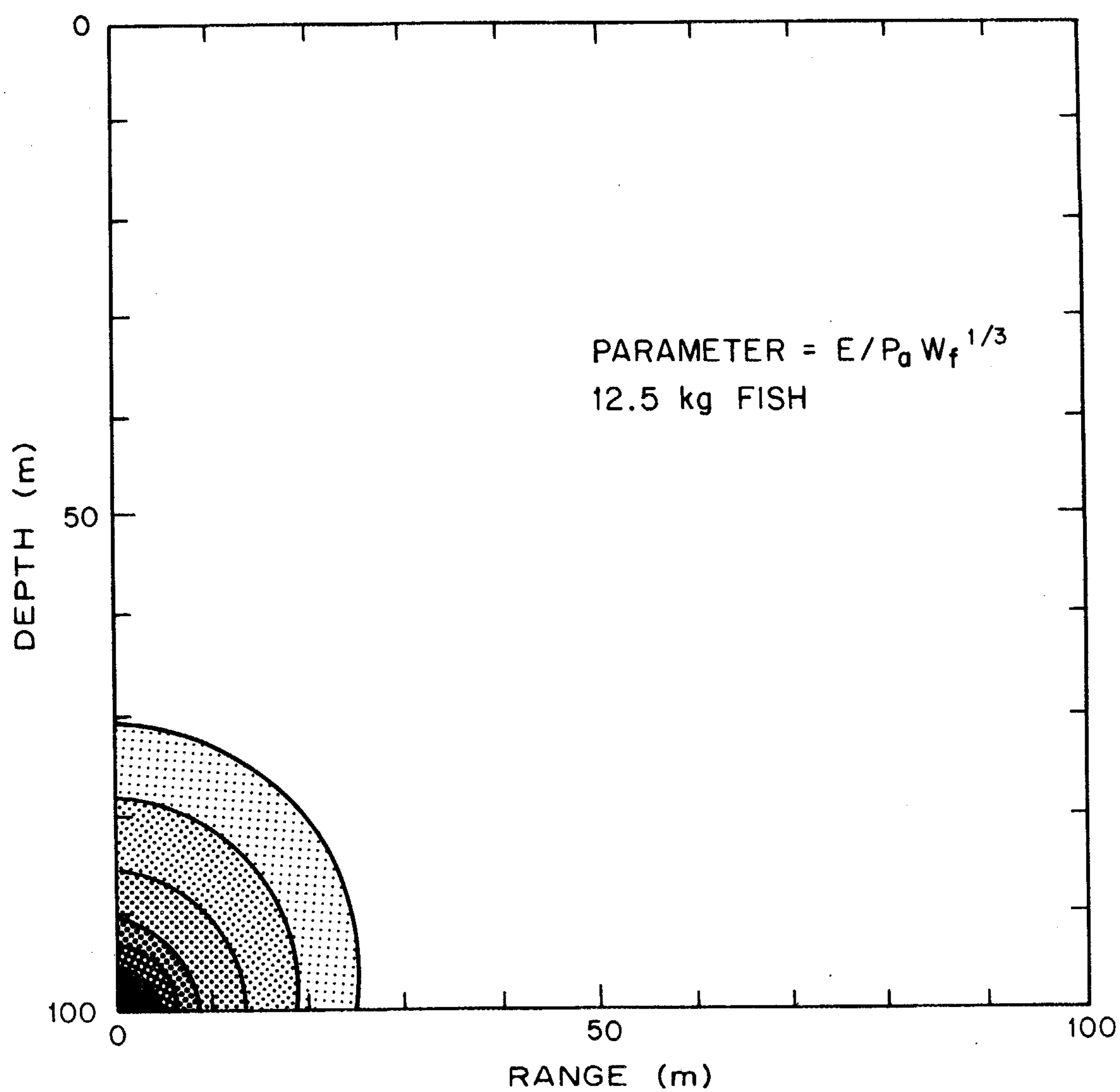

FIG. 20 Contours of kill probability vs. range and depth for 12.5 kg fish and 11.3 kg charge at 100 meters depth assuming log $(E/P_a W_f^{1/3})$ as parameter.

Organization, Scientific Council Meeting, June 1981 (NAFO SCS Doc. 81/VI/15). Data on individual net tows or local concentrations of fish are also available from survey vessel cruises and from interviews with fishermen. Other information has been obtained by research submersible observations and surveys with side-scan sonar and underwater TV.

To determine the worst possible case of fish kills from an explosion one needs to consider density spread and possible depth of fish schools. Since the killing range is so much greater for small fish at their depth of maximum vulnerability, those pelagic species such as herring in which small fish are sometimes found in large schools at such depths should be considered more carefully. Average numbers of many kinds of fish may be estimated from the National Marine Fisheries Service 20-year old groundfish survey program. In the survey program sampling has been conducted on a stratified random method. However, local concentrations are more likely to be observed by fishermen who actively search for actual schools than by surveys taken at random. In order to properly evaluate fishermen's catch records, it is useful to know something about fishing methods. For this purpose the report by Allen et al. (1976) is an excellent reference.

b. Fishing Methods

On Georges Bank five or six times as many fish are caught near the bottom by otter trawls as are caught anywhere else in the water column. For this reason the species primarily caught in this way are called ground-fish. This method of fishing on the bottom accounts for cod, pollock, haddock, hake and all flatfish. Although some ground fish species move off the bottom, the deployment of the otter trawl from a

TABLE III

Fisheries Reports for Georges Bank

Weight in Metric Tons

	1980	1979	1978	1977
Ground Fish				
Principal Groundfish	142,279	125,244	144,197	153,582
Flounders	53,706	44,442	39,592	39,709
Pelagic Fish				
Herring	83,251	64,880	59,920	52,199
Mackerel	1,640	1,151	1,196	5,410
Swordfish	903	1,206	2,148	589
Menhaden	68,669	58,728	43,455	15,833

NOTE: Otter Trawls generally used to catch ground fish. Purse Seines used to catch pelagic fish

All weights taken from Subarea 5 - Georges Bank

Northwest Atlantic Fisheries Organization Reports (NAFO SCS Doc. 81/VI/15) and equivalent reports for prior years.

single vessel requires contact of the trawl doors with the bottom to properly spread the net. Therefore, the fishing is better at times and places where the fish congregate near the bottom.

Most of the remaining fish, herring, mackerel and menhaden are caught near the surface by purse seines or sometimes in midwater by pair trawling. Long lines catch fish in mid-water but are not presently used on Georges Bank except for some pelagic fish such as swordfish, which form a very minor part of the fishery. Detailed data on volume filtered in specific deployments of a seine or a pair trawl together with quantities caught were not available from our consultants who were all experienced only in bottom fishing with the otter trawl. The New England fishermen mainly use otter trawls for herring as well as for bottom fish. Some use high opening nets which fish 20 fathoms off the bottom. The Soviets are one of the few nations to employ purse seines to surround the herring school which is most efficient.

c. Pelagic Fish

The Atlantic sea herring (Clupea harengus) and the silver hake (Merluccius bilinearis) are two commercially important pelagic fish species harvested on Georges Bank. These species are susceptible to the effects of underwater explosions since they both possess swim bladders, and both may be found at any level in the water column.

Between the years 1960-1970 a large herring fishery developed off Georges Bank eventually led to almost a total depletion of the species. The large schools of herring caught by large foreign fishing vessels while purse seining and pair trawling on the surface and in mid-water have not been seen since 1980. Recent catch rates do not reflect the

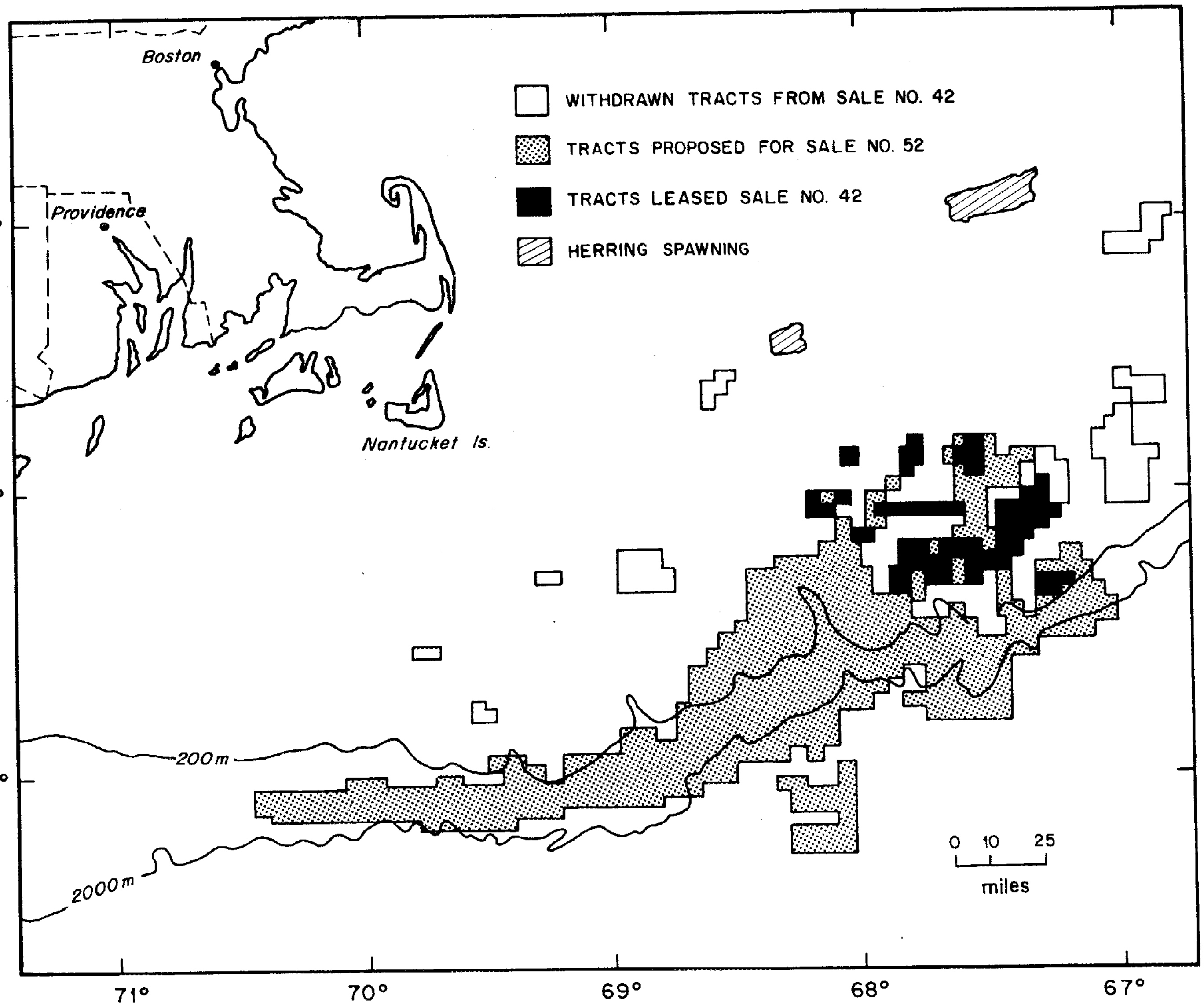

FIG. 21 Chart of lease areas on Georges Bank showing lease sites and herring spawning areas.

abundance which this species once occupied on the bank, but if not disturbed the species might recover.

During the summer months, herring feed on Georges, and generally are found approximately at the 250 ft. contour or less. During the winter months most of the herring schools go south and inshore. In the fall they migrate in deeper water where they gather to spawn. Around late October they are ready to spawn and they select gravelly bottom on which to deposit their eggs, (Anthony et al., 1970). (One of such prime spawning grounds is north of Cultivator Shoal in deeper water 20-30 fathoms). No spawning exists around the southern edge of Georges. Hatching occurs within 12-18 days after which the developing larvae swim to the surface and there attain their adult morphology in two to eight months.

Research conducted by the USSR since 1964 indicate that the size of the spawning stock has been declining, resulting in fewer spawning grounds. Spawning was scattered in 1969 producing smaller diffuse patches of eggs suggesting that the spawning population continued to decline (Anthony, 1969). To give the herring the best chance of recovery, it would be desirable to avoid drilling or explosive wellhead severance on herring spawning grounds. Figure 21 shows the position of the spawning grounds (Anthony et al., 1970) relative to the present lease areas. If the lease areas are not expanded, there appears to be no conflict.

Silver hake, also called whiting, are so widely distributed and abundant over the continental shelf of eastern North America that the population would probably not be significantly affected by localized kills from well severance explosions.

d. Groundfish

For concentrations of ground fish near the bottom there is much more data. Otter trawls on the bottom are used in surveys by the National Marine Fisheries Service and by commercial fishermen. Grosslein (1969), Sissenwine and Bowman (1978) and Clark (1979) describe these surveys. Catches by random trawling are much smaller than average or best hauls reported by commercial fishermen who actively search for concentrations of desirable fish. Fishermen find it very useful to keep and refer to their fishing logs. They report that similar concentrations of desirable fish recur year after year in the same locations at the same season. These reports suggest that actual fish concentration at drilling locations are probably much less than those estimated from the heaviest net tows.

It is possible, however, that the drilling may attract some species of fish. Gilmor et al., 1981, report such an effect for red hake and spotted hake on Exxon's block 684 off New Jersey. These are very different fish with very different habits than the above mentioned silver hake. They made side-scan sonar and TV observations before and after this block was drilled. On the first post-drilling survey they found "a zone approximately 150 meters in diameter where drill cuttings and other debris were visible in scattered patches that increased in size as the former well site was approached." They found that hake (Urophycis) within 500 meters of the well site were about 10 times more numerous ($1.8/m^2$) than they were before drilling and that beyond 500 meters of the well site hake were still about twice as numerous as before.

e. Fish Densities

To calculate fish densities from trawl net hauls it is necessary to determine volume of water filtered by the net. Herding effects of the ground cables and escape response are also important. Carrothers (1980) discusses herding effects and gives dimensions for commonly used nets. Most sources agree that three knots relative to the water is a reasonably accurate towing speed for most trawls. This is about 5600 meters/hr. The Yankee 36 is the most commonly used trawl. Wingspread of this net when towed is about 10 meters. Herding effect of the ground warps might increase the effective width to about 17 meters. The height of the opening is about two meters. Our estimate of effective volume filtered is thus 5600x17x2 or 190,000 cu meters/hour, or perhaps half this considering various losses. Reports from fishermen interviewed indicate that a very good haul might catch 10,000 lbs/hour while an average haul might catch about 1000 lbs/hour. If we take the smaller estimate of volume filtered and the larger estimate of catch, we calculate a maximum fish density of about .1 lb/cu meter or .05 kg/cu meter.

Gilmor et al., 1981, found a maximum concentration of hake after drilling of 1.8 individuals per sq. meter. They do not say how far from the bottom the hake were found, but assuming two meters or less we get a density of about one individual per m^3. If the average weight of a hake is .5 kg this would be .5 kg/m^3 or about 10 times the density we estimate from fishermen's trawl records. The predrilling density would be about the same as our maximum trawl density. However, Gilmor et al.

do not report the size of the hake that they saw. While .5 kg is a good weight for an adult hake, the average is probably considerably less.

VI. ECOLOGICAL IMPORTANCE OF FISH KILL FROM EXPLOSIONS USED FOR OIL WELL SEVERANCE

Data from the Northwest Atlantic Fisheries Organization Table III lists catch data from an area slightly larger than Georges Bank. Document NATO SCS 18/VI/15 from which the 1980 data were abstracted lists for the year 1980, the catch data by region where caught and by flag country of the fishing vessels. The total catch on Georges Bank of all finfish was 3.8×10^5 metric tons of which 1.4×10^5 metric tons were principal groundfish, i.e., cod, haddock, redfish, hake and pollock. 6.2×10^4 metric tons of cod were caught, i.e., the maximum tonnage of any single species.

Georges Bank is approximately elliptical with major axis 120 nm and minor axis 100 nm and average depth of 25 meters. If we assume these dimensions the volume of water over the bank is approximately 3.3×10^{12} cubic meters. If we assume that the species susceptible to explosive damage are primarily the principal groundfish and that there are probably at least one hundred times as many there as are caught each year, we get a mean density of less than 4×10^{-3} kg/m^3.

The weighted kill-volume calculated from Figure 17 was about 1.6×10^5 m^3, about equal to the volume filtered by a one-hour tow of a 36 trawl. However, most of volume included in Figure 17 is in a mid-water or near-surface regions where one would not expect to find the concentrations of groundfish that are swept up by the trawl. We may reasonably expect that a well-severance explosion will kill fewer fish than a one-hour trawl tow.

Gussey (1977) gives a general catch summary up to 1973 for the Georges Bank region. He quotes a total catch of all species of fish for 1973 of 2×10^9 lbs, approximately 10^6 metric tons. He quotes Wise (1974) that maximum sustainable yield for cod alone is probably at least 75×10^6 lbs, i.e., 3.4×10^4 metric tons. From 1962 to 1980 the yearly catch of cod as reported by ICNAF has equalled or exceeded this figure. The catches from 1977 through 1980 were nearly twice this weight, which suggests that Wise's estimate may have been low.

The probable kill from oil well severance is clearly several orders of magnitude less than the fishing mortality. Considering these numbers, it does not seem likely that a few explosions per year would have any serious ecological significance.

Although the average fish kill from a well severance explosion should not be large, it is recommended that the area be checked for large schools of fish before setting off an explosion, since some pelagic fish, such as herring, normally swim in very large dense schools that can be detected by fish finders. If by rare chance such a school happened to be in the area, a large kill could occur. We would recommend use of a boat with an acoustic fish finder immediately before and after a severance explosion, and divers or underwater TV to check the bottom. If large numbers of dead or disabled fish are not seen after a reasonable search, one could be confident that the kill was minimal.

List of Figures

Figure 19. Contours of kill probability vs. range and depth for 2.5 kg fish and 11.3 kg charge at 100 meters depth assuming log $(E/P_a W_f^{1/3})$ as parameter. Note on pressure release (see Fig. 17) also applies to this figure.

Figure 20. Contours of kill probability vs. range and depth for 12.5 kg fish and 11.3 kg charge at 100 meters depth assuming log $(E/P_a W_f^{1/3})$ as parameter.

Figure 21. Chart of lease areas on Georges Bank showing lease sites and herring spawning areas.

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